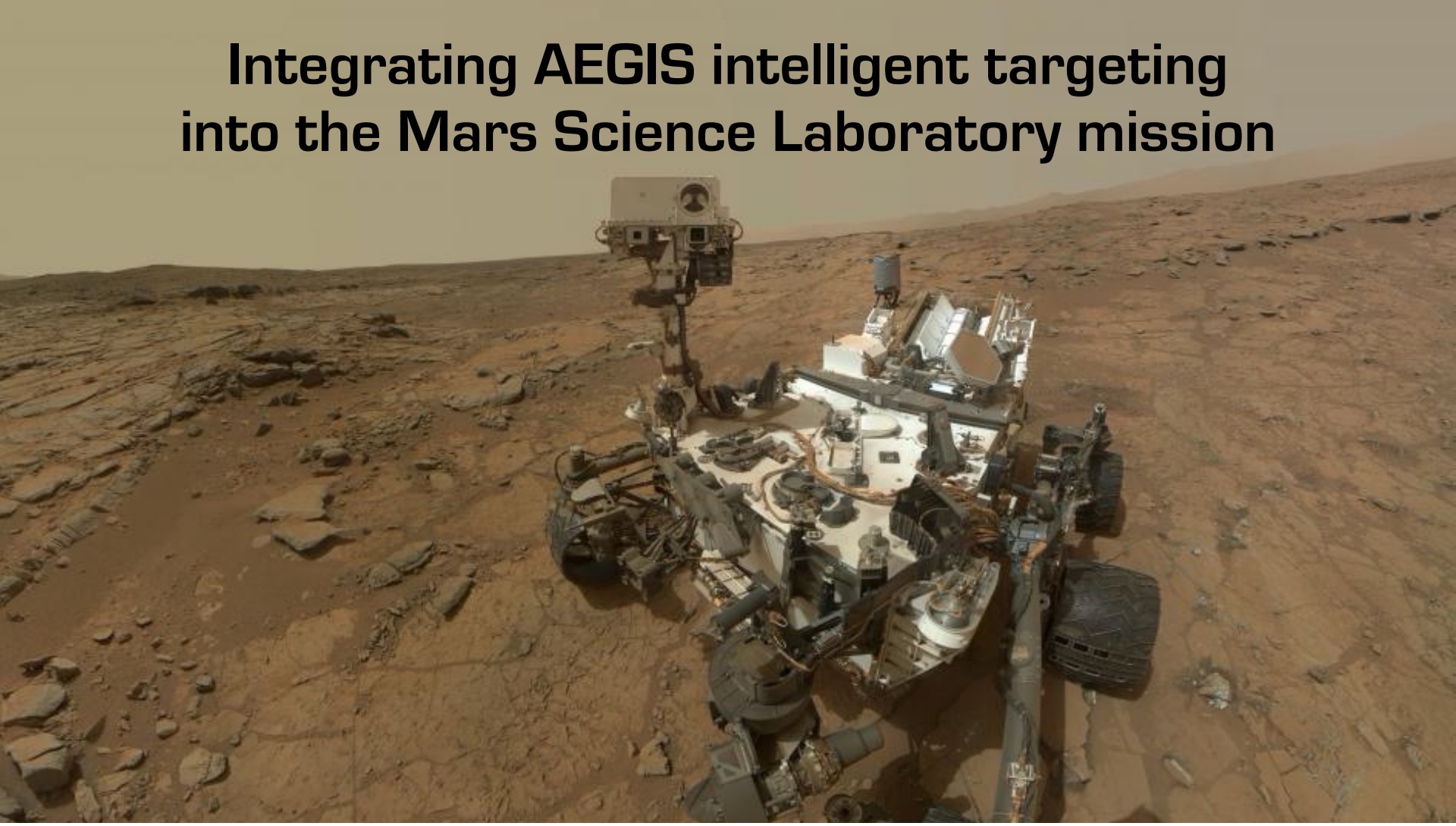
Integrating AEGIS intelligent targeting into the Mars Science Laboratory mission



Raymond Francis

For the AEGIS team
Jet Propulsion Laboratory,
California Institute of Technology

Introduction to AEGIS

AEGIS is:

An **intelligent software** system

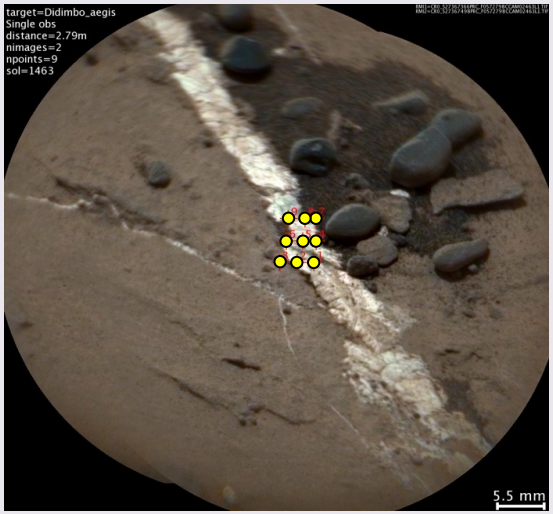
Running since 2016 **on-board** the *Curiosity* rover

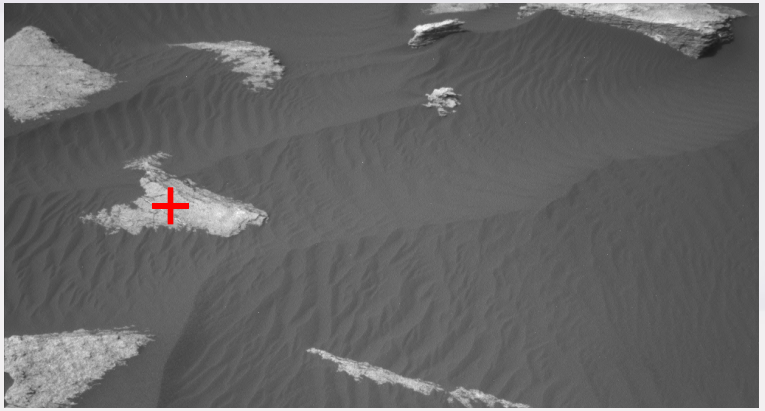
Autonomously choosing science targets and measuring them with the ChemCam laser spectrometer instrument

Favouring targets based on **scientists' preferences**

Regularly, reliably interpreting **complex natural scenes**

Consistently performing well even in unexplored terrain





AEGIS Intelligent Targeting System

"Automated Exploration for Gathering Increased Science"

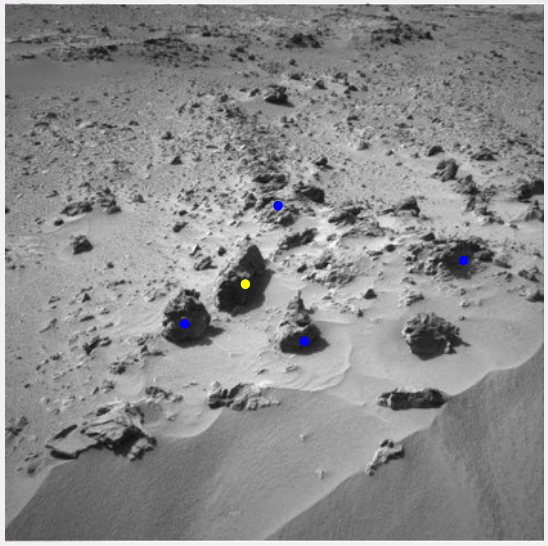
AEGIS was first flown on MER Opportunity in 2010

- Autonomous target selection for PanCam (mid- or post-drive)

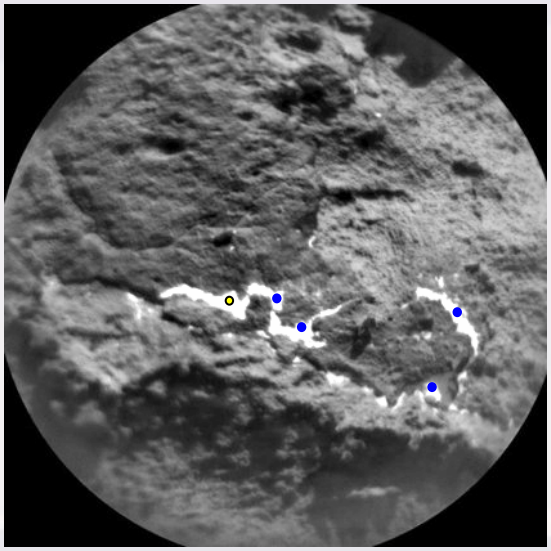
Now in use for ChemCam on MSL, in two roles

- Autonomous target selection in NavCam images
- Autonomous pointing refinement in RMI images

NavCam

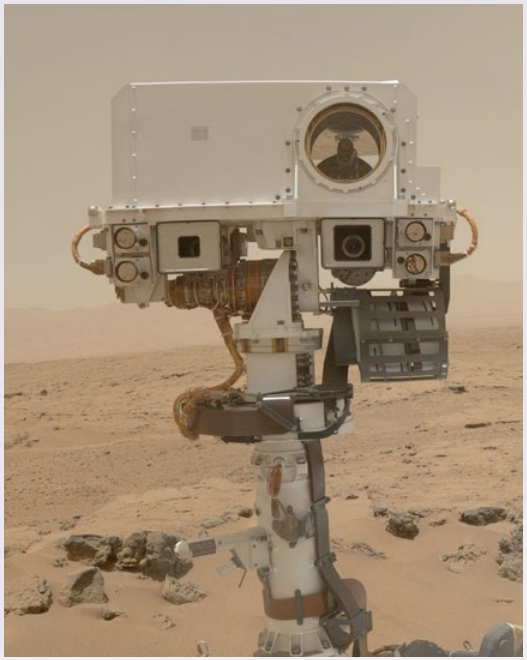


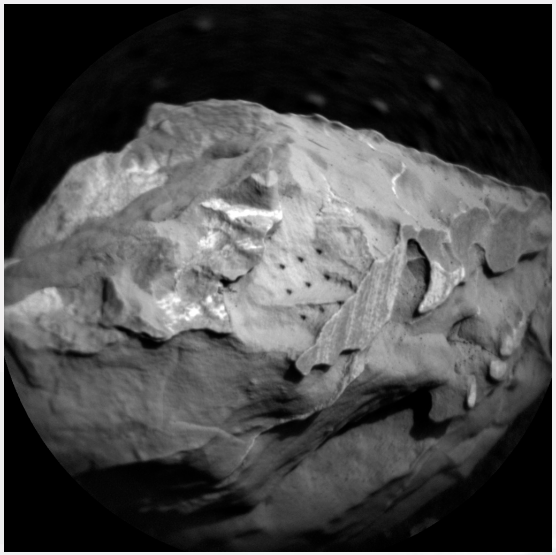
RMI



ChemCam Instrument

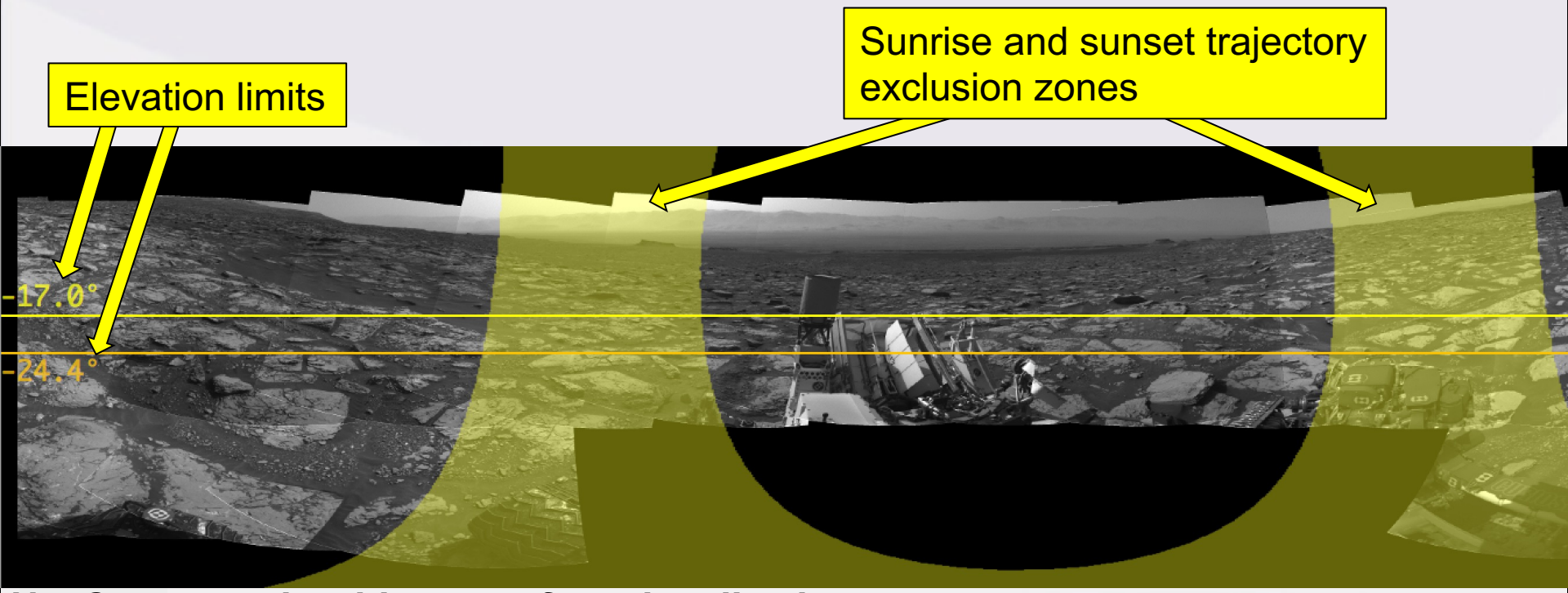
- Laser-Induced Breakdown Spectrometer (LIBS) with Remote Micro-Imager (RMI)
- Gives geochemical composition of rock targets at ranges up to 7 metres
- Over 550,000 measurements on 1700 targets on Mars since 2012
- Joint development of
  - Los Alamos National Laboratory (LANL, Los Alamos)
  - Institut de Recherche en Astrophysique et Planétologie (IRAP, Toulouse)





ChemCam Sun Safety

- ChemCam can be damaged by pointing at the sun
- Targets must be in safe pointing zones
- Slews between targets must also protect the instrument
- AEGIS must protect ChemCam

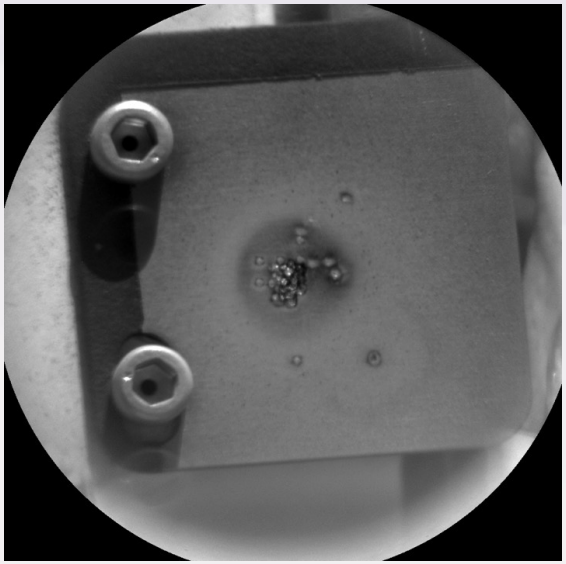


NavCam mosaic with sun-safety visualization

Planners must choose targets which are safely away from the sun.

ChemCam Collision Safety

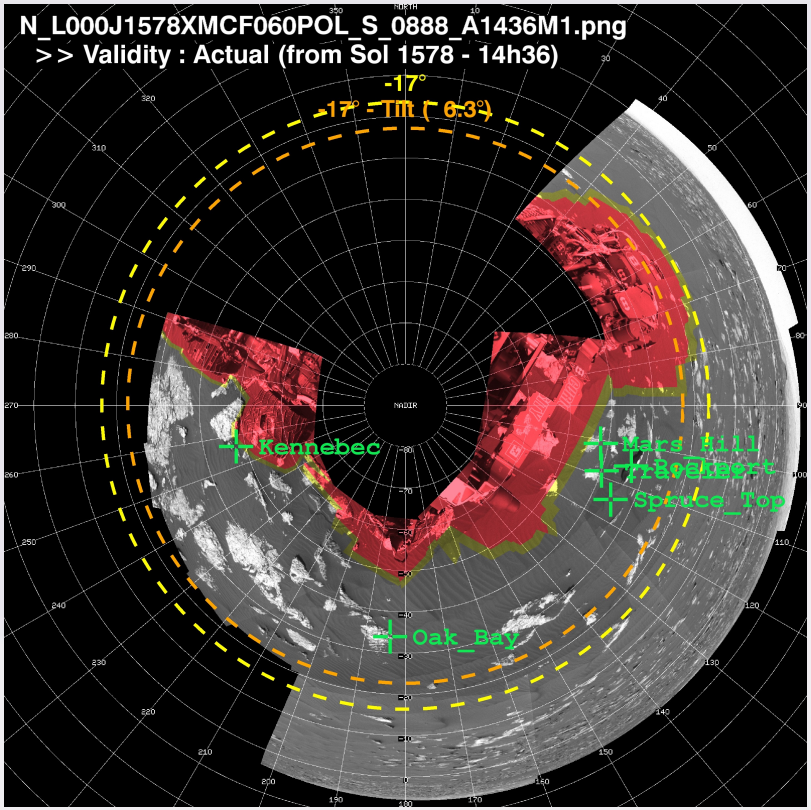
- Don't shoot the rover!
- AEGIS must recognize and reject unsafe pointings
- Onboard model of rover articulation



ChemCam calibration target, sol 1126

This is what happens when ChemCam's powerful laser hits a plate made of solid titanium.

It is important to prevent ChemCam from shooting the rover anywhere but on the calibration target.

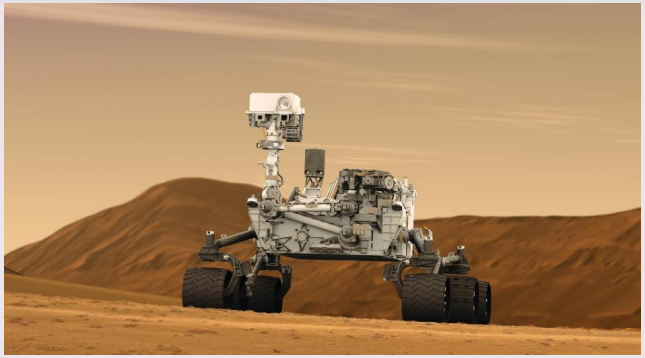


ChemCam collision check graphic

ChemCam PULs model proximity of targets to the rover in angular space. Sometimes, detailed modeling by Rover Planners is needed.

The current NavCam mosaic is plotted in polar co-ordinates; exclusion zone (the rover body) is shaded red and yellow.

MSL Infusion Challenges



- *Curiosity* hardware and software complexity
- New safety constraints compared to MER
  - Sun-Safety
  - Collision
- Limited onboard memory
  - 256 MB of DRAM, 128 MB of RAM – AEGIS limited to 16MB
- Flight processor: RAD750 @ 133 MHz
  - AEGIS runtime: 2-5 minutes
  - Stereo information on targets is time consuming
- First technology to use MSL component load (similar to loading a flight software patch)
  - Navigating a new process for the flight system
- Want to limit operations complexity
  - New commands need to be intuitive for operators to use
  - Telemetry should be easily understandable

Building confidence

So we were thinking of turning control of the powerful laser over to the computer. Cool?

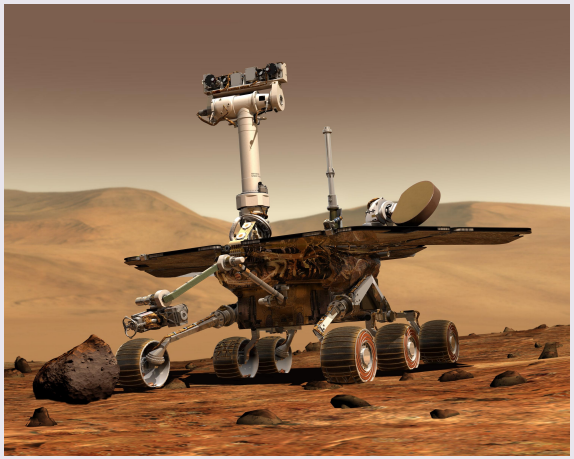
Building confidence

So we were thinking of turning control of the powerful laser over to the computer. Cool?

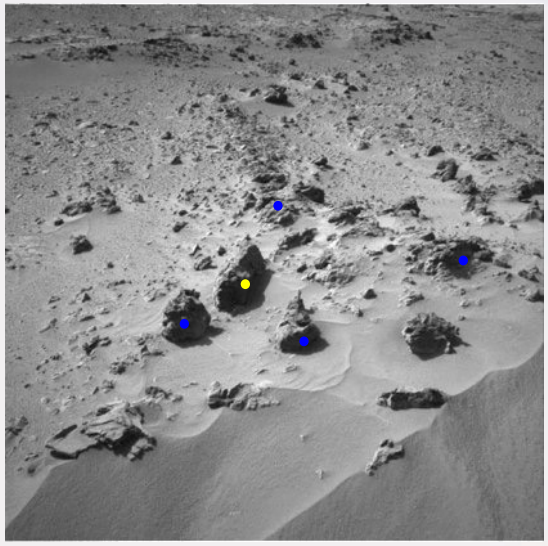
We promise this won't cause *Problem(s)*

The argument from heritage

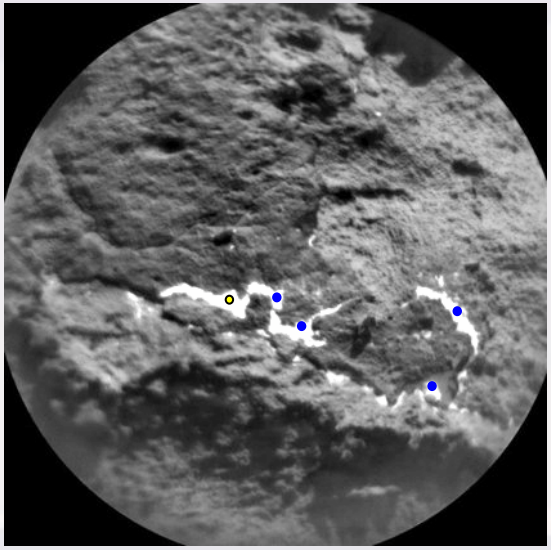
- Successful demonstration and use on the MER Opportunity rover
  - Ran safely, successfully acquired PanCam images
- Also demonstrated the algorithm on images from MSL



NavCam

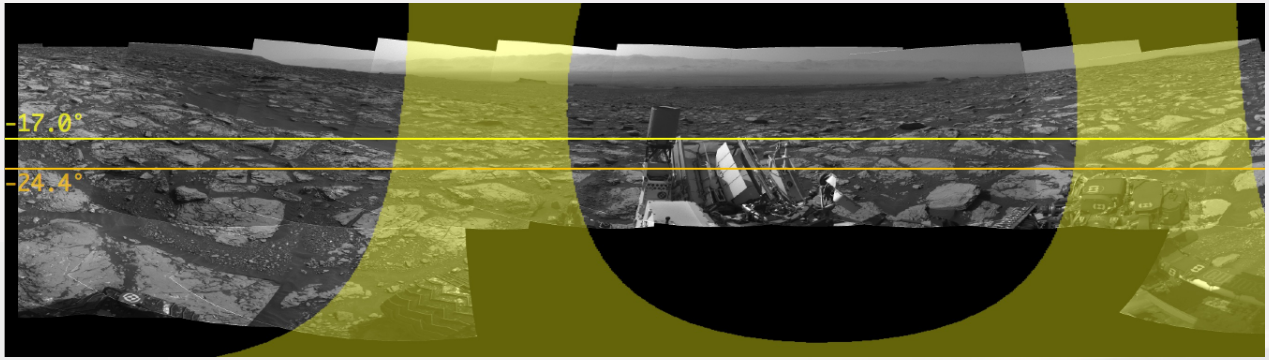


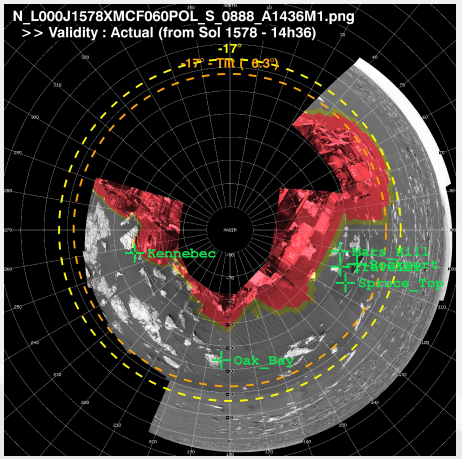
RMI



Work with existing safety rules

- *Curiosity* has on-board collision and sun-safety checks
  - AEGIS does not change or replace these
- An AEGIS run is entirely self-contained, including its own safety checks.
  - Commands generated by AEGIS are then subjected to the mission-level checks.
  - AEGIS' internal checks ensure no selected target would be rejected and waste time onboard
- Minor duplication, but avoids changing trusted safety systems

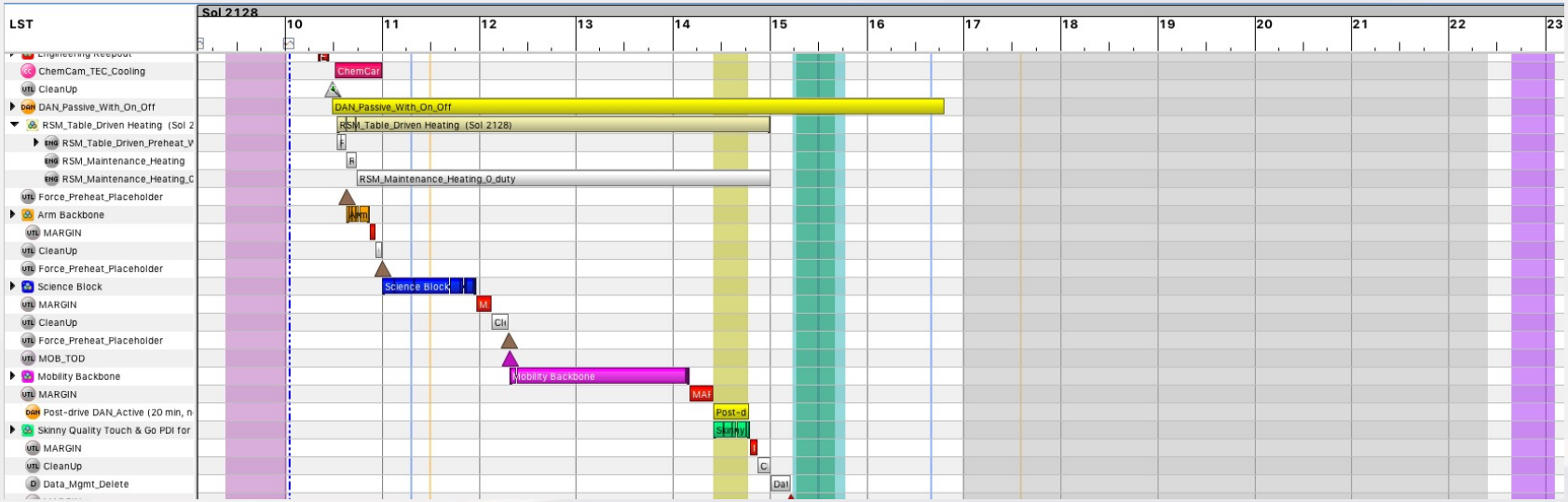




Verify interactions

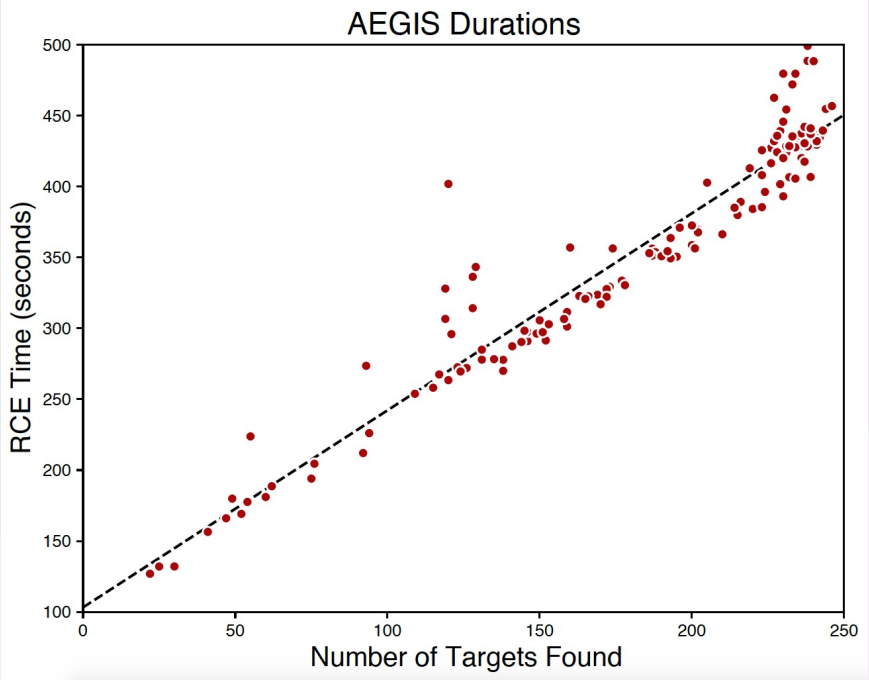
- MSL is a very complex mission
  - The rover does a lot of things, often at the same time
  - Variability in execution time

- Plan for, and test parallelism – when AEGIS runs concurrent with other activities
  - Verify effects on AEGIS, and other activities
  - Ensure AEGIS can run in parallel with the right things
  - Make lists of allowed/disallowed parallel activities



Constrain resources

- Show that the execution is bounded
  - AEGIS has a maximum allowed amount of RAM
  - Each “Find Targets” run is constrained by a timeout limit
  - Allow the mission-level FSW to interrupt AEGIS
    - Added “AEGIS Cleanup”



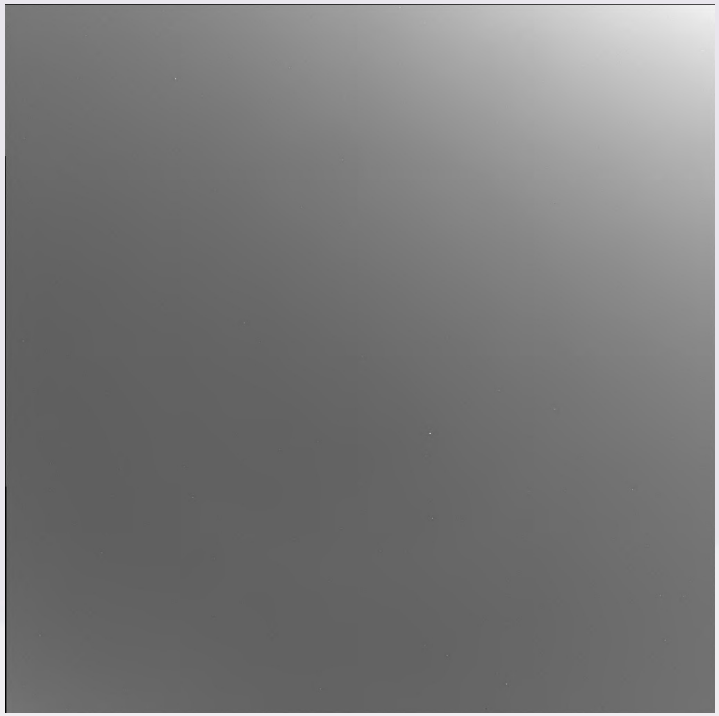
Plot of AEGIS Find-targets durations

The distribution is well-characterized, but also subjected to a hard duration limit.

Values shown here are for NavCam runs on the flight model rover.

Plan for faults

- Be robust to probable and improbable failures
  - No targets found
  - No allowable targets
  - Source image corrupted
  - ChemCam marked “sick”
  - Exceed duration limit
- Demonstrate that AEGIS “Exits gracefully” in all cases



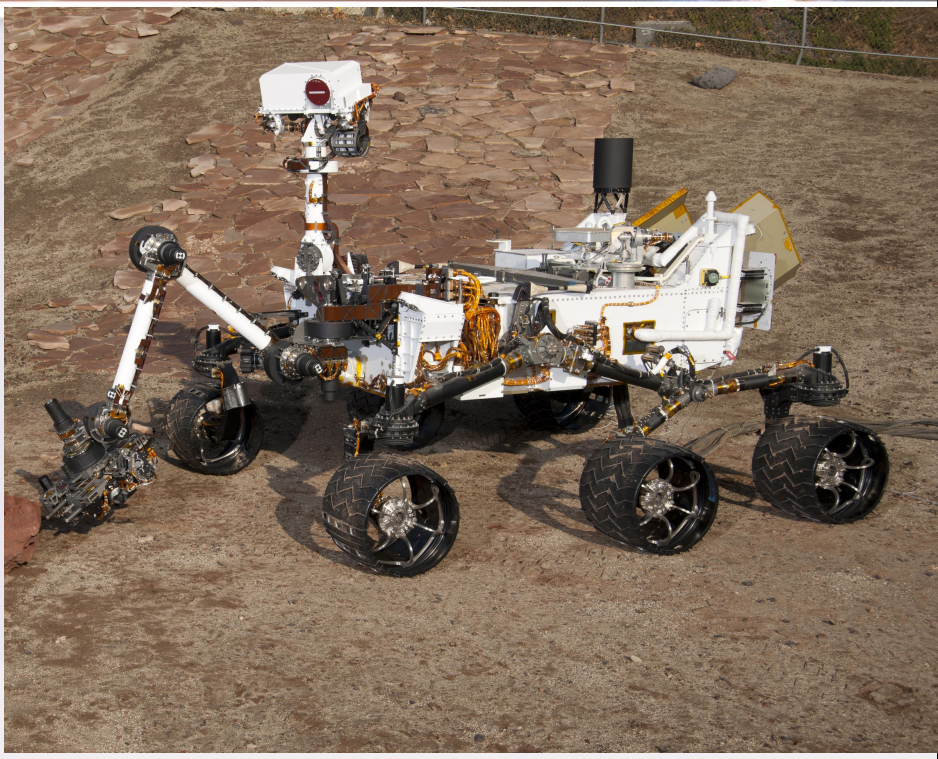
NavCam image of the sky

What happens if AEGIS tries to find rocks in this?

Answer: There are no rocks, but everything is fine.

Verification and validation

- Test at every level
  - Each command
  - Each operation
  - Each function
  - The full process end-to-end
  - Under the range of conditions
  - With parallelism during key events
- Use appropriate test venue
  - MSL software simulator (WSTS)
  - MSL hardware simulator (VSTB)



MSL Vehicle System Test-Bed

The VSTB is a high-fidelity hardware simulator of the Curiosity rover. It's shown here in the JPL Mars Yard

Onboard checkouts

- Progressive, stepwise checkout of capabilities

  1) Take source image, find targets

  2) … and point ChemCam at the target, but just acquire an image

  3) … and point ChemCam, then fire the laser and complete a science sequence

- For each version
  - RMI source image (autonomous pointing refinement)
  - NavCam source image (autonomous target selection)

- Finally, both together
  - Find, select target in NavCam, acquire RMI, centre on vein therein

The first AEGIS-guided LIBS target

Target Warmbad on sol 1191 has its 5-point LIBS raster centred directly across the light-toned vein, as desired.

Science Team buy-in

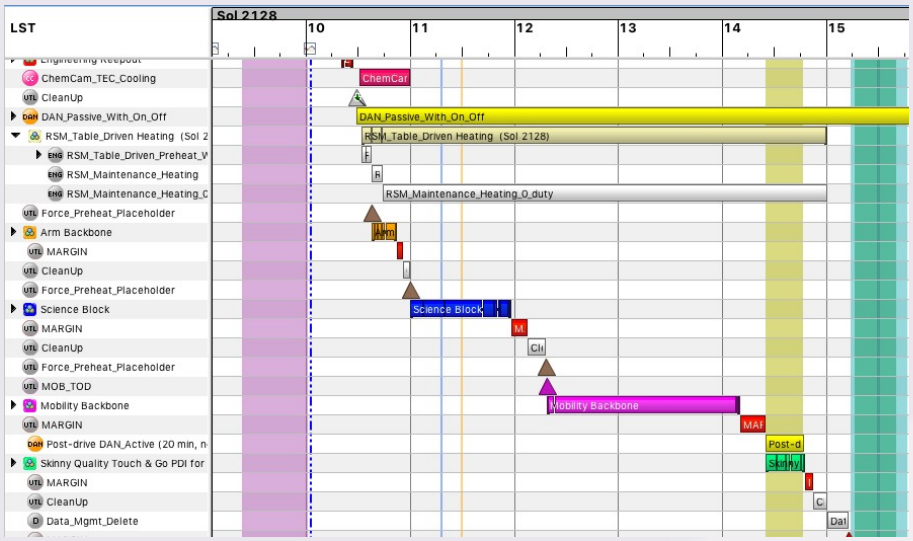
- Could not have succeeded without support from the mission Science Team
  - ChemCam PI support
  - Clear communication of the motivation and value (to science!) of the technology
  - Several presentations introducing the capability
  - Training for ChemCam & MSL ops personnel, and for scientists
- Provide support, and be available!
  - Concise documentation easily at hand in ops
  - AEGIS support mailing list
- Integrated work
  - Member of AEGIS team trained as ChemCam instrument PUL and joined the uplink ops team.

Training and familiarization plan

Training for operators on each relevant mission subsystem and role, and familiarization for the entire science team. Periodic updates and refreshers.

Make it easy to use

- Minimize operations complexity
  - Balance versatility with ease of use
  - Make sun-safety and collision a no-effort concern for the operator
- Staged rollout
  - Introduce basic capabilities, then add more options
- Automatic command expansion
  - Users set parameters in MSLICE GUI, scripts expand to sequences with no hand editing.
  - Templated activities do not require any parameter changes for use.
  - Changes are permitted, for occasional new or special use

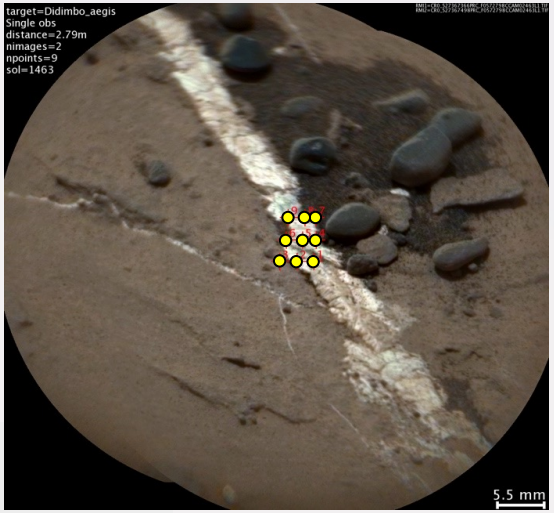


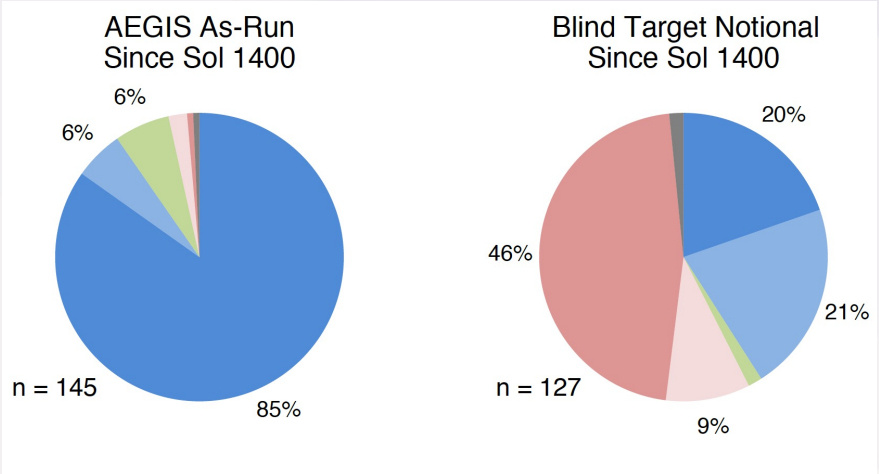
MSLICE planning

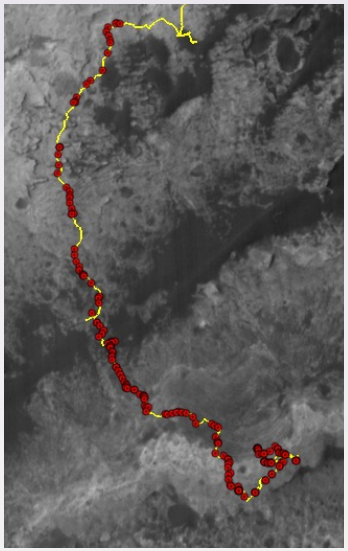
AEGIS activities can be added as easily as ground-targeted ChemCam observations.

Outcomes

- AEGIS team is very pleased with system performance to date
  - Feedback from science team has been very positive
  - 3 ‘pointing-assured’ targets
  - 171 ‘bonus observations’
  - AEGIS-guided observations often inform next sol’s tactical decisions
  - Learning new ways to explore

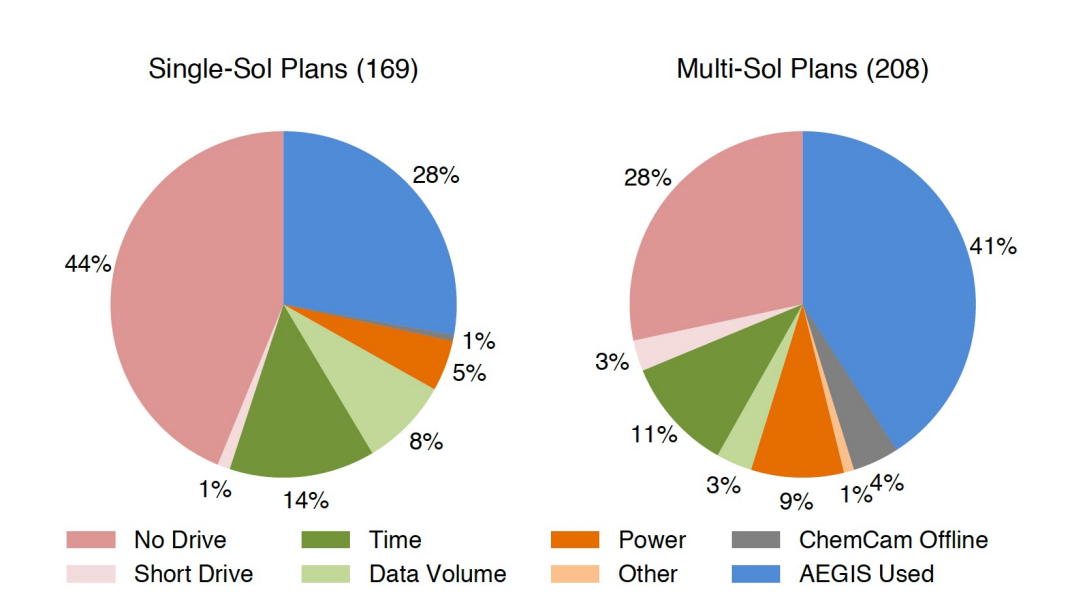






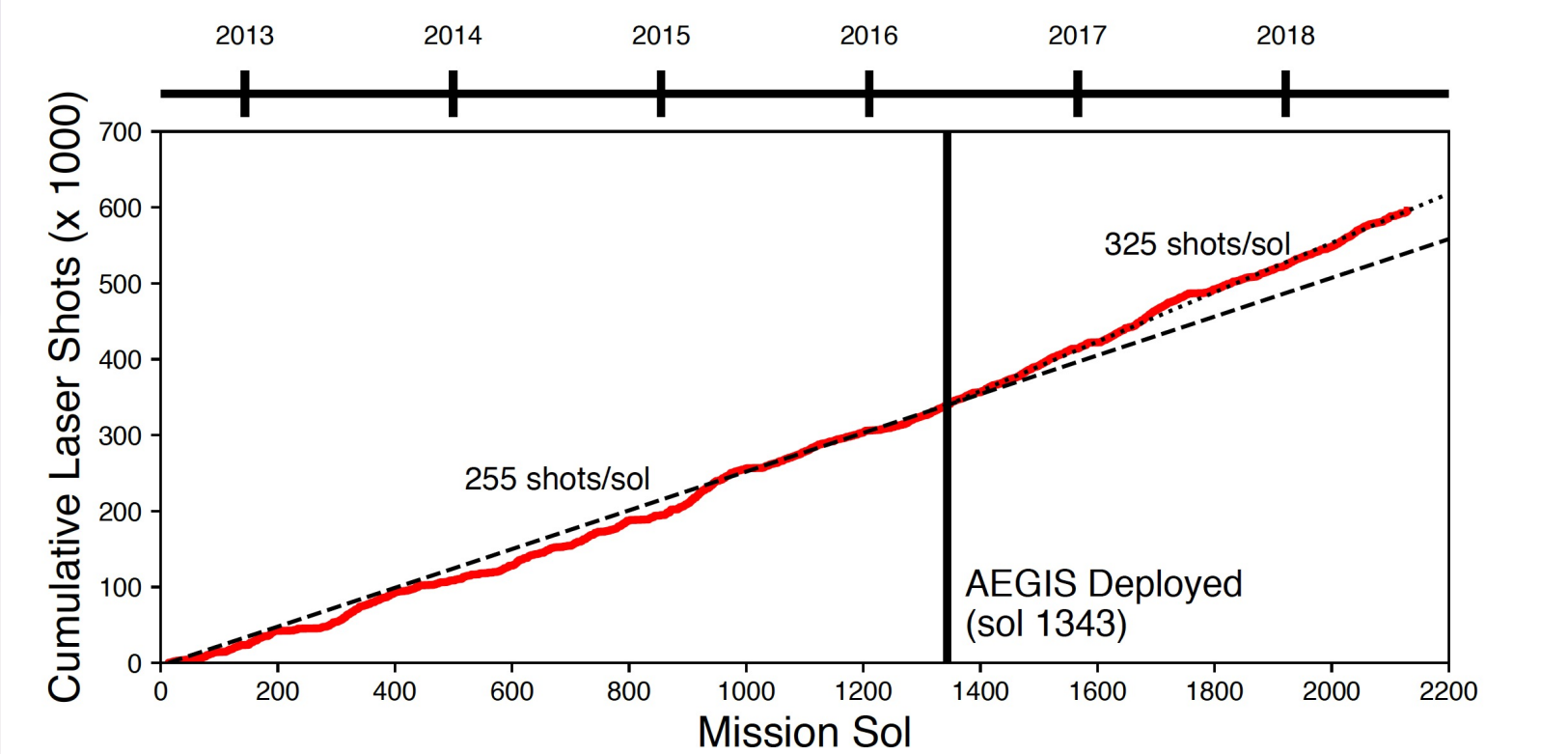
Frequent use

- Charts for **all plans** since sol 1343
  - When AEGIS was used, or why it wasn't



- **When there is a drive**, and ChemCam is available, post-drive AEGIS is used in
  - 55% of all plans
  - 59% of multi-sol plans
  - 49% of single-sol plans

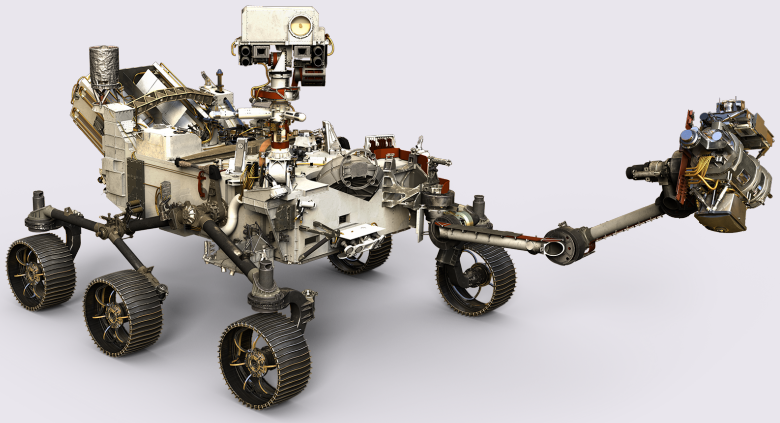
More data from ChemCam



- Significant increase in rate of data return from ChemCam
- AEGIS rollout to science team on sol 1343

Future

- AEGIS is baselined for Mars 2020
  - SuperCam, the successor to ChemCam
  - Other mast-mounted instruments



- In this case, the winning features were:
  - Demonstrated science value to Mars Science Laboratory
    → Science Office and Instrument team support
  - Projected ops efficiency savings for ambitious surface mission
    → Mission System support
  - Low development cost to adapt MSL AEGIS flight code to M2020
    → Budget acceptability

AEGIS deployment & Ops team

AEGIS deployment relied on AEGIS, MSL, and ChemCam teams:

AEGIS
Tara Estlin (AEGIS PI)
Daniel Gaines
Raymond Francis
Gary Doran
Vandi Verma
Benjamin Bornstein
Michael Burl

And of course:
Larger AEGIS development team
ChemCam ops personnel
MSL engineering ops team
MSL science ops team

ChemCam
Roger Wiens (ChemCam PI)
Steven Johnstone
Suzi Montaño
Olivier Gasnault
Laurent Peret
Eric Lorigny
Diana Blaney
Jens Frydenvang
Valérie Mousset

MSL
Deb Chattopadhyay
Betina Pavri

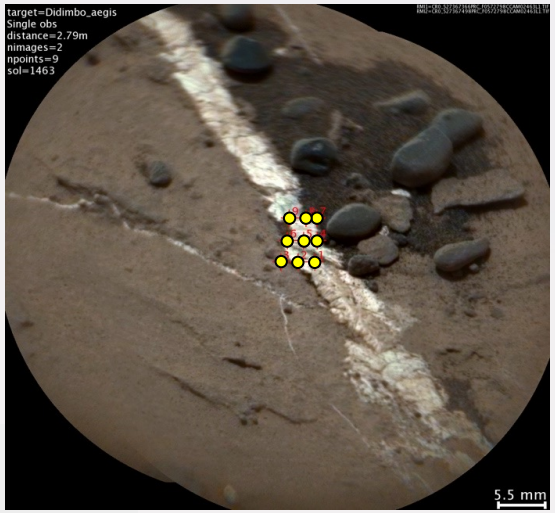
Backup slides

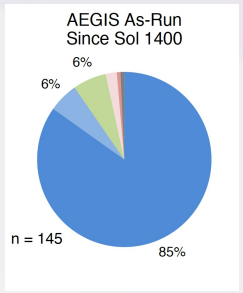
Deployment timeline

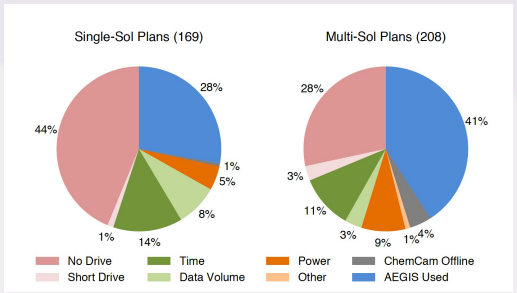
- AEGIS ChemCam implementation fully tested, verified, and validated 17 Sep 2015
- AEGIS software uploaded to MSL 29 Sep 2015
- AEGIS software installed to MSL flight software 10 Oct 2015
- 7-step progressive checkout process
  - Nov 2015 – Jan 2016
  - Piecewise in between ongoing science mission activities
- Science and Ops team training, tools update: Feb – Apr 2016
- AEGIS approved for routine science team use May 2016

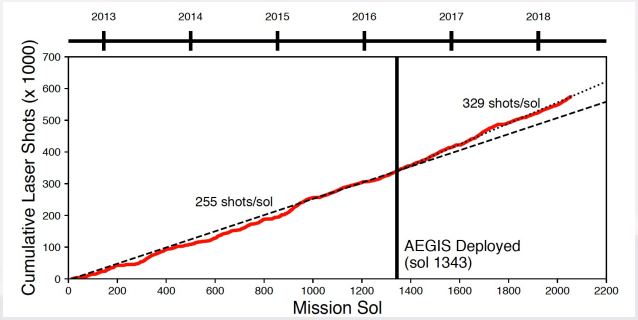
Conclusions

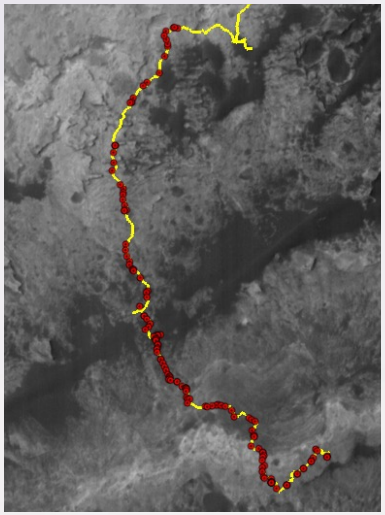
- AEGIS team is very pleased with system performance to date
  - Feedback from science team has been very positive
  - 3 ‘pointing-assured’ targets
  - 171 ‘bonus observations’
  - AEGIS-guided observations often inform next sol’s tactical decisions
  - Learning new ways to explore











Fundamentals

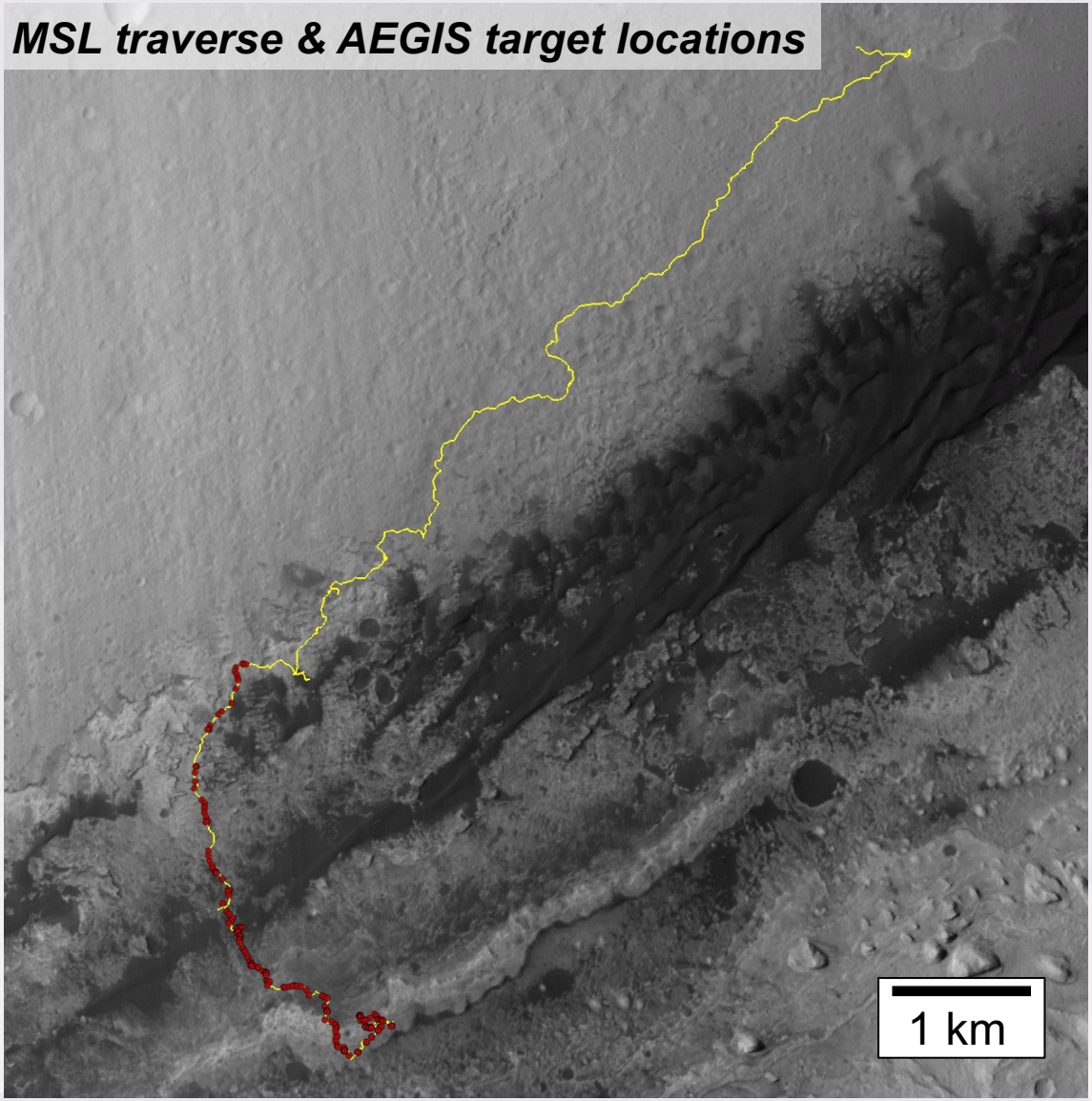
In 150 runs on Mars…

- AEGIS has consistently done these
  - Successfully analyzed the source image and identified geological targets
  - Chosen the specified number of targets
  - Returned a ChemCam RLR observation on chosen target(s)

- AEGIS has never done these
  - Triggered a collision warning
  - Triggered a sun-safety warning
  - Given ChemCam a poor focus seed (could cause bad LIBS/RMI data)

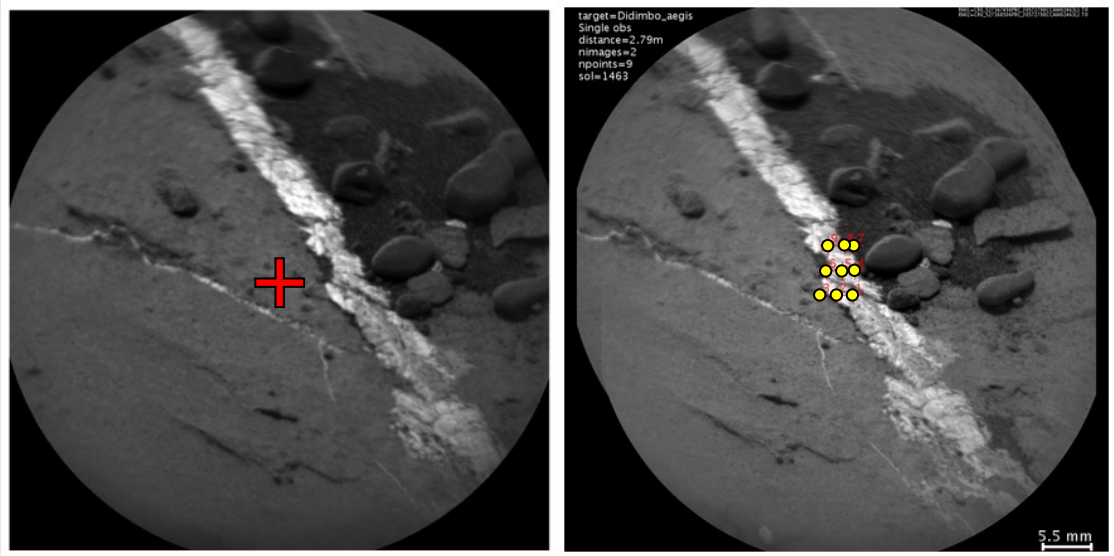
Use by the Science Team

- First used sol 1343
  (planned on 13 May 2016)
- Results here as of sol 2054
  (planned 16 May 2018)
- Post-drive NavCam version:
  150 runs, 171 targets
- Pre-drive RMI version:
  3 runs
- Total MSL odometry since rollout: 6.859 km



Results: Pointing refinement

- Three uses
- In two cases, initial (ground-selected) pointing missed target entirely
- AEGIS corrected pointing and hit the target in all three cases
- For the two misses, pointing refinement saved the observations – a manual retargeting second attempt would have been necessary. Not possible if rover were to drive in that plan



ChemCam target Didimbo, sol 1463

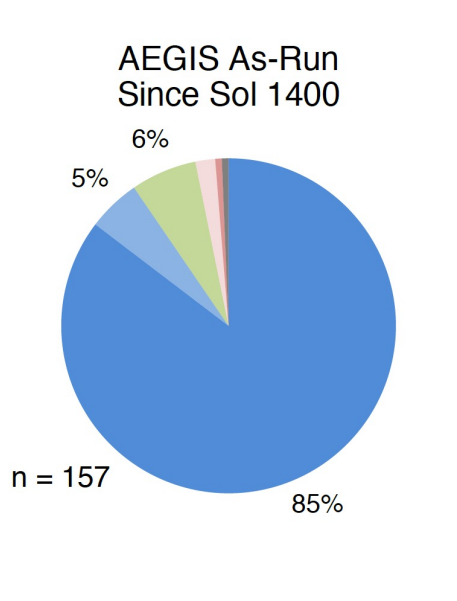
AEGIS corrected a ~3 mrad pointing error, achieving the desired LIBS measurement of the vein.

RMI FOV diameter: 20 mrad
Target profile: Bright vein features
Distance: 2.79 m

Results: Target selection

For the post-drive targets…

- ChemCam on AEGIS' top-ranked target (or top 2 if time allows)
- Hits clean outcrop 85% of runs since sol 1400 parameter update



Results: Target selection

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- Hits clean outcrop 85% of runs since sol 1400 parameter update
- Exceptions:
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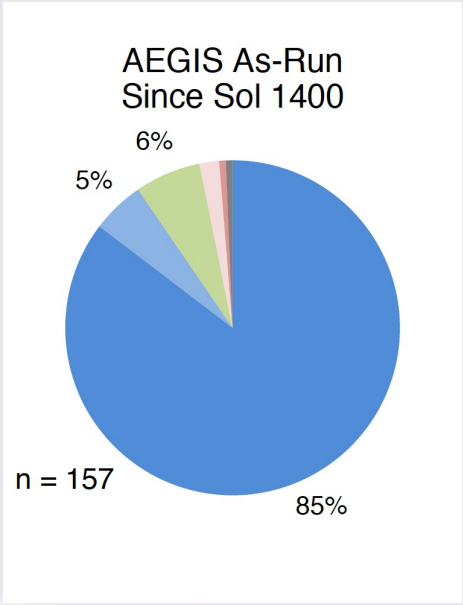
  - Chose a float rock or other material (usually when there is little outcrop in view)



Results: Target selection

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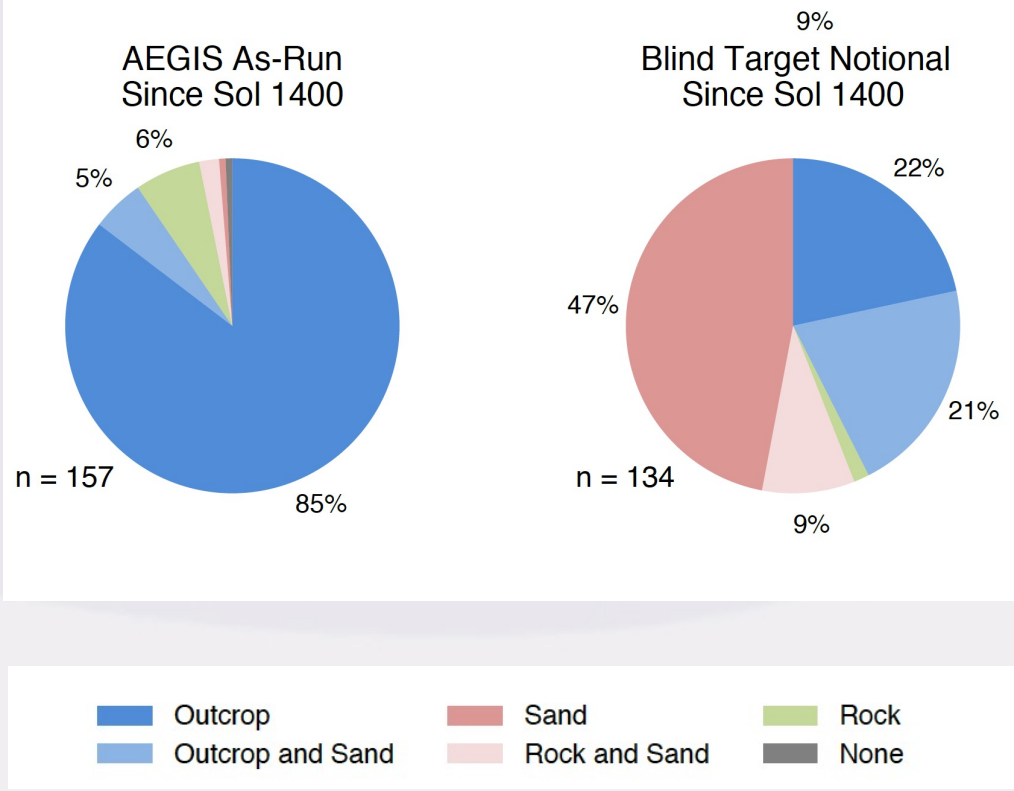
- ChemCam on AEGIS' top-ranked target (or top 2 if time allows)
- Hits clean outcrop 85% of runs since sol 1400 parameter update
- Exceptions:
  - Chose desired outcrop unit, but some shots hit sand on top or beside the outcrop
  - Chose a float rock or other material (usually when there is little outcrop in view)
- Modeled Blind Targeting results for same sols:
  - 10x1 RLR @ standard pointing
  - Only one target



New approaches and strategies

- Sharing work between operators on Earth and the autonomous system
  - AEGIS sequences are easy to plan, saving effort in ops planning
  - Let AEGIS do what it does well, so humans can focus on what they do well
- Doing more with limited time
  - Unlocking the post-drive period for remote LIBS/RMI
  - Complete work that doesn't fit in the targeted science block
- Opportunistic and serendipitous science
  - More data means more discoveries
- Quicker data delivery to enhance decision-making
  - LIBS data when we previously only had images
- Working when humans can't
  - Uplink constraints, downlink constraints, holidays

Sol 1612: Highest chlorine

Highest concentration of chlorine ever measured by ChemCam on Mars

(So high it strains the calibration)

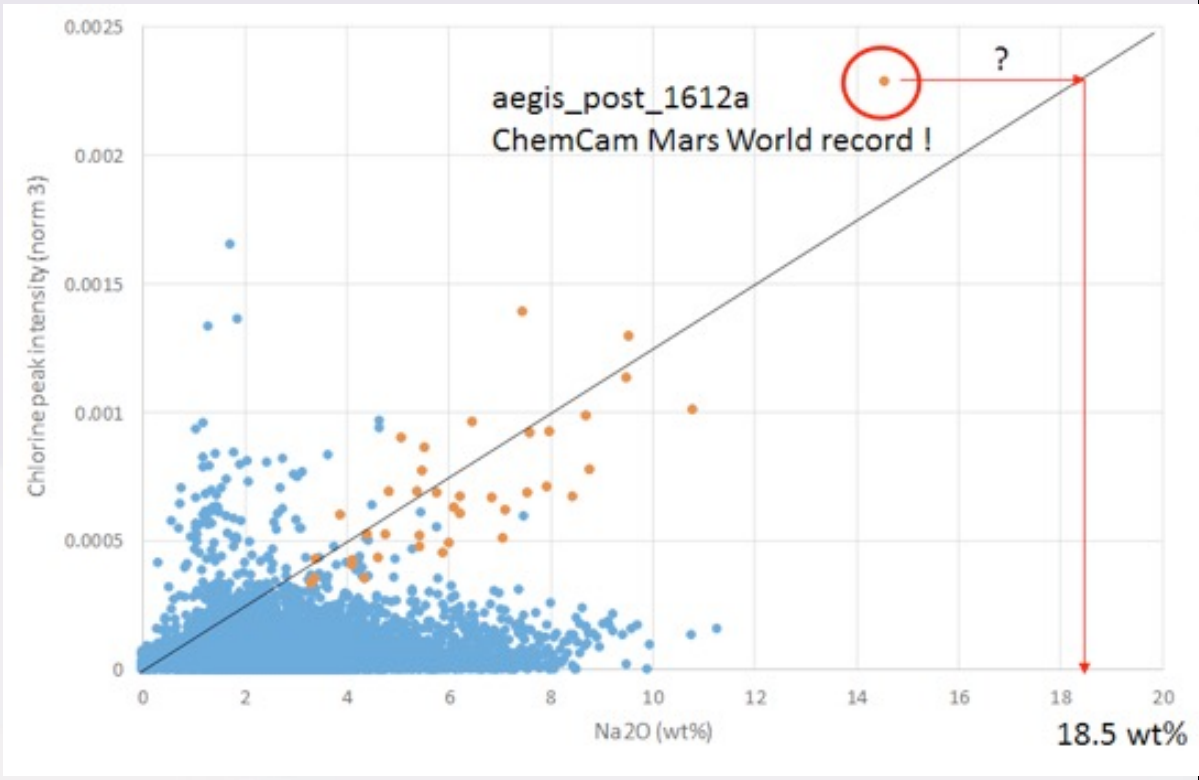


Figure from Pierre-Yves Meslin

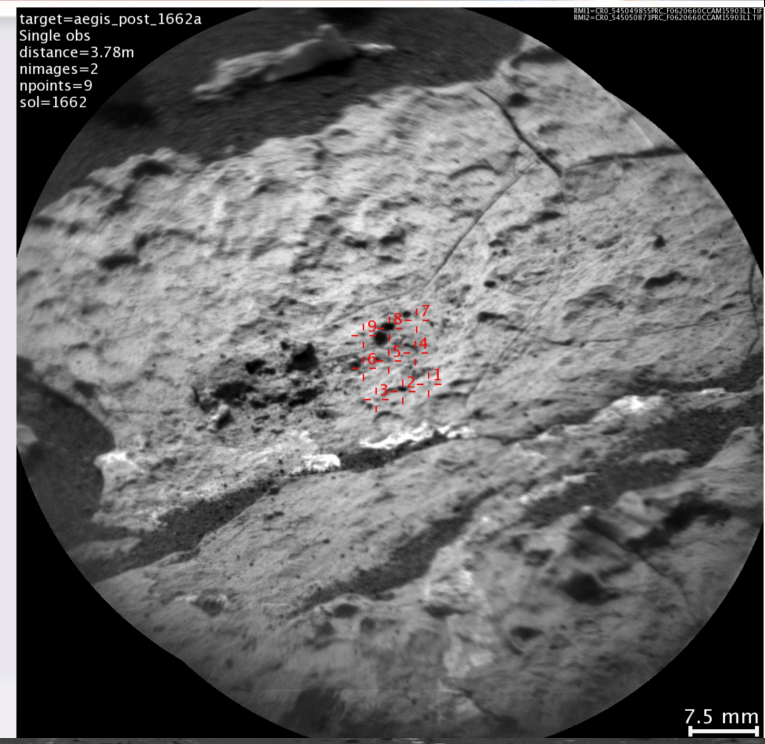
Notable events

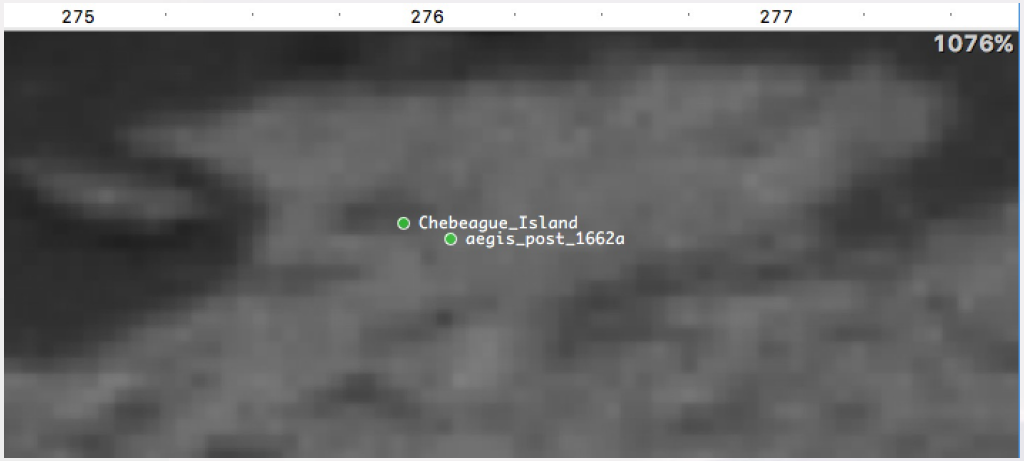
Sol 1662: Finding unusual chemistry

Rock was visually unremarkable

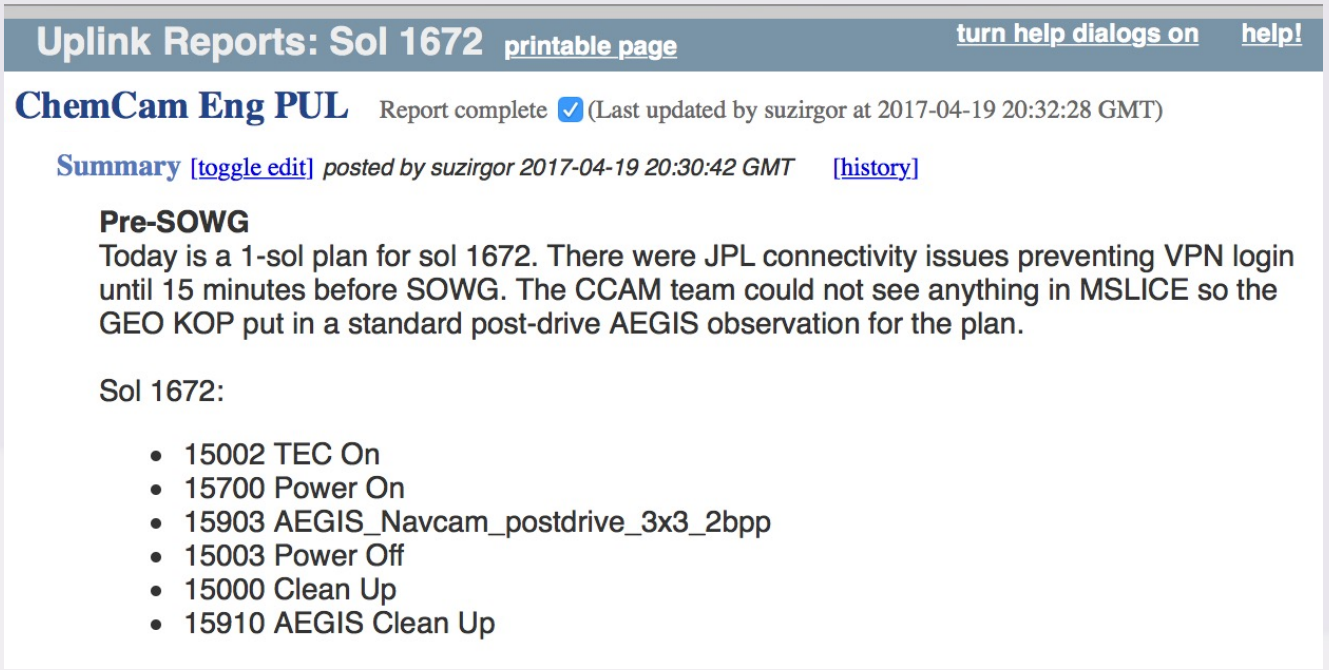
Points 5 & 8 had notable chemistry for the local bedrock, with certain elemental abundances unusual

Team spent a targeted observation revisiting this spot.





Notable events



Uplink Reports: Sol 1672 printable page turn help dialogs on help!

ChemCam Eng PUL Report complete (Last updated by suzirgor at 2017-04-19 20:32:28 GMT)

Summary [toggle edit] *posted by suzirgor 2017-04-19 20:30:42 GMT* [history]

Pre-SOWG

Today is a 1-sol plan for sol 1672. There were JPL connectivity issues preventing VPN login until 15 minutes before SOWG. The CCAM team could not see anything in MSLICE so the GEO KOP put in a standard post-drive AEGIS observation for the plan.

Sol 1672:

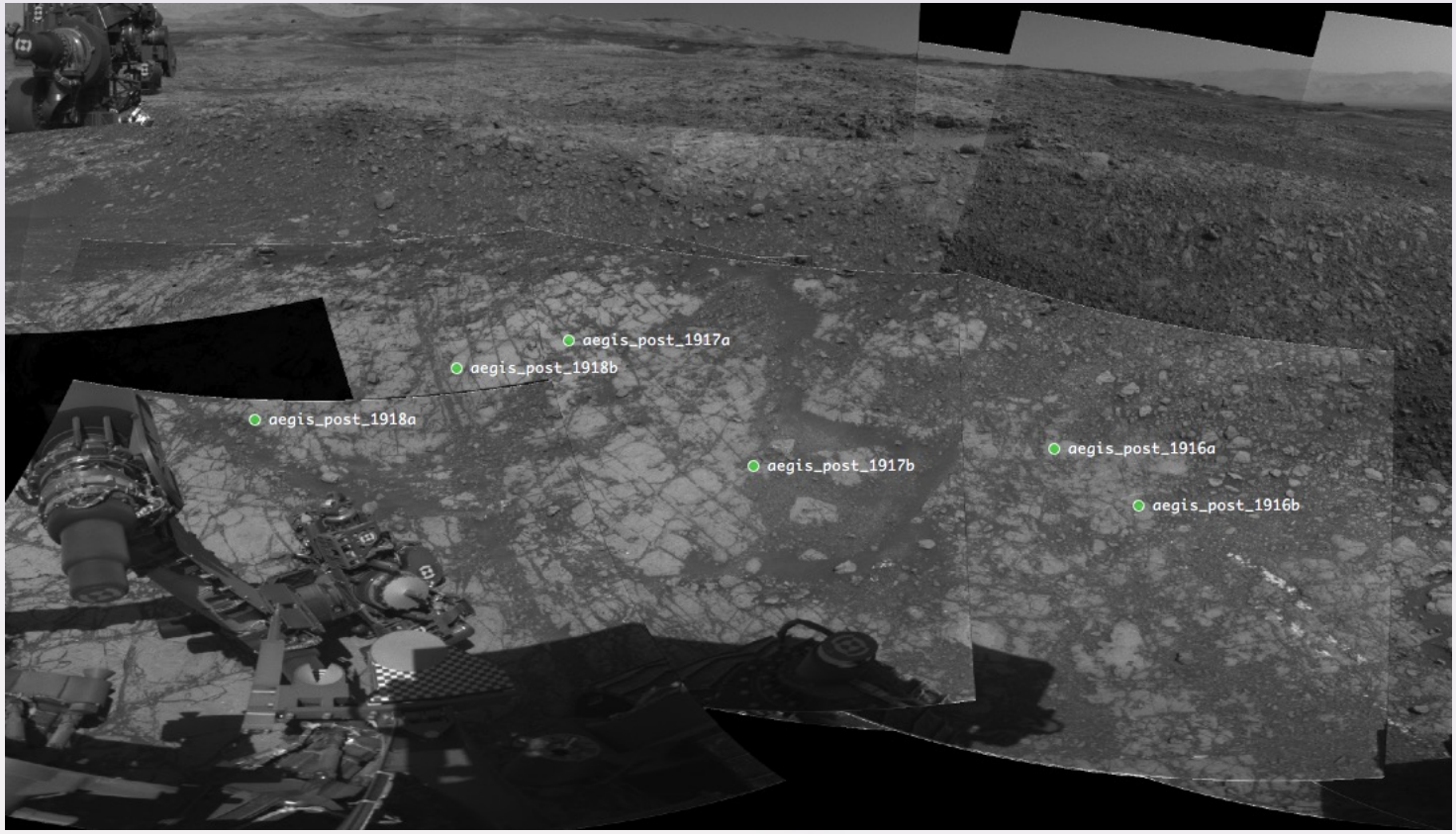
- 15002 TEC On
- 15700 Power On
- 15903 AEGIS_Navcam_postdrive_3x3_2bpp
- 15003 Power Off
- 15000 Clean Up
- 15910 AEGIS Clean Up

Sol 1672: Networking problems

Problems on the ground kept operators from being able to safely target instruments on Mars.

AEGIS-guided ChemCam observations were the only kind possible.

December 2017 holiday plan



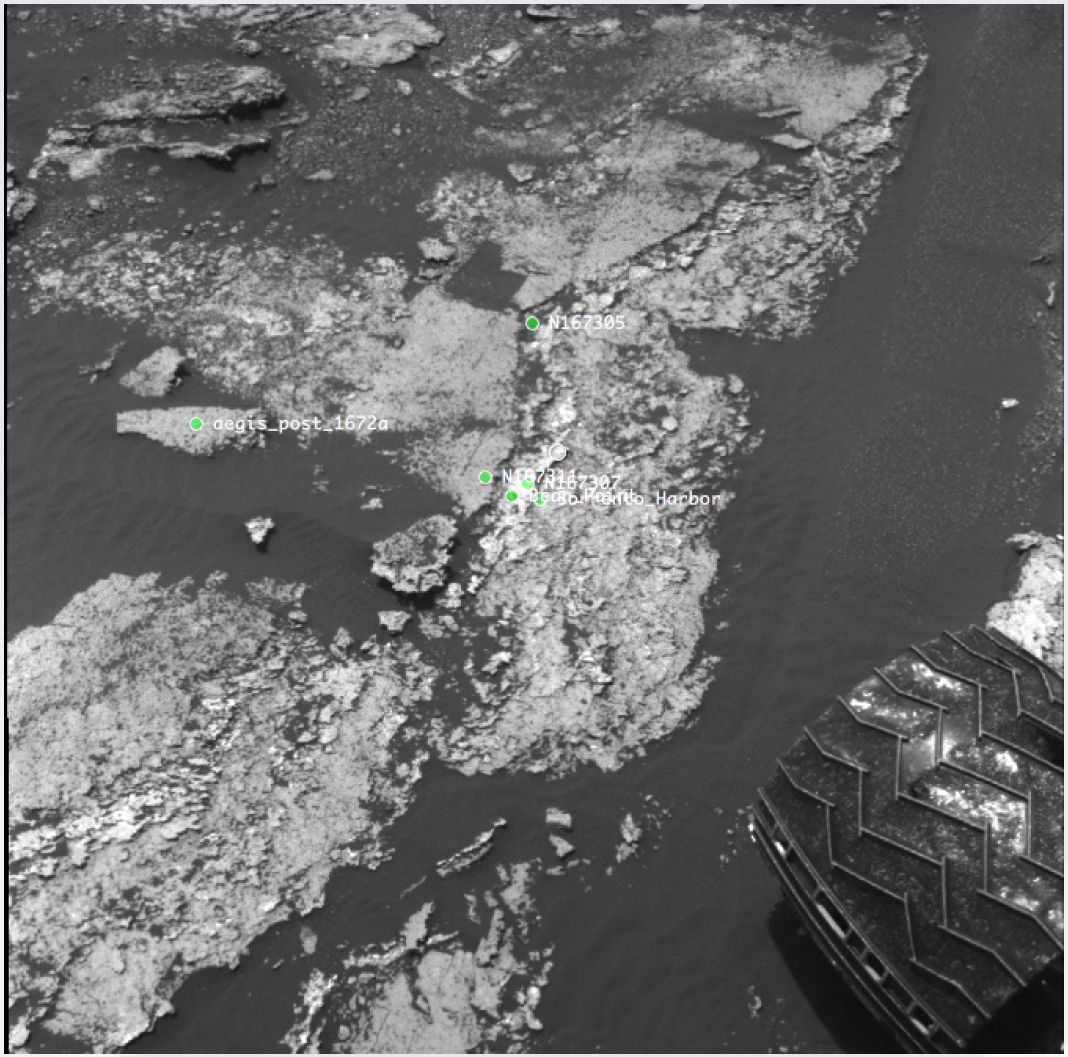
Six targets measured on 3 sols of an 8-sol plan, while mission planning on Earth was stood down.

Notable events

Sol 1673: Collect all 3

Upper, smooth material
Brighter vein
Lower, rough material

AEGIS had already measured the upper unit, allowing a complete survey with only 2 targeted measurements

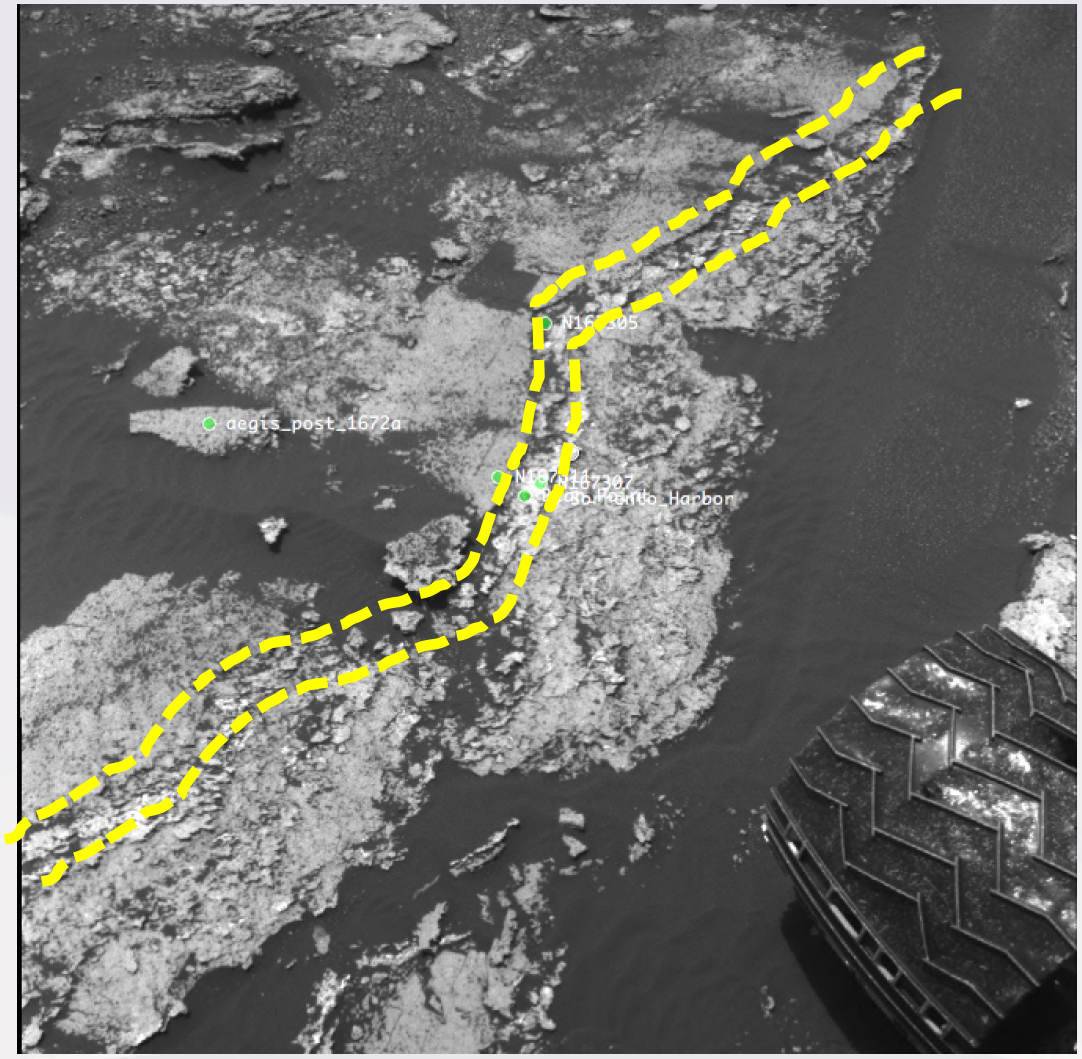


Notable events

Sol 1673: Collect all 3

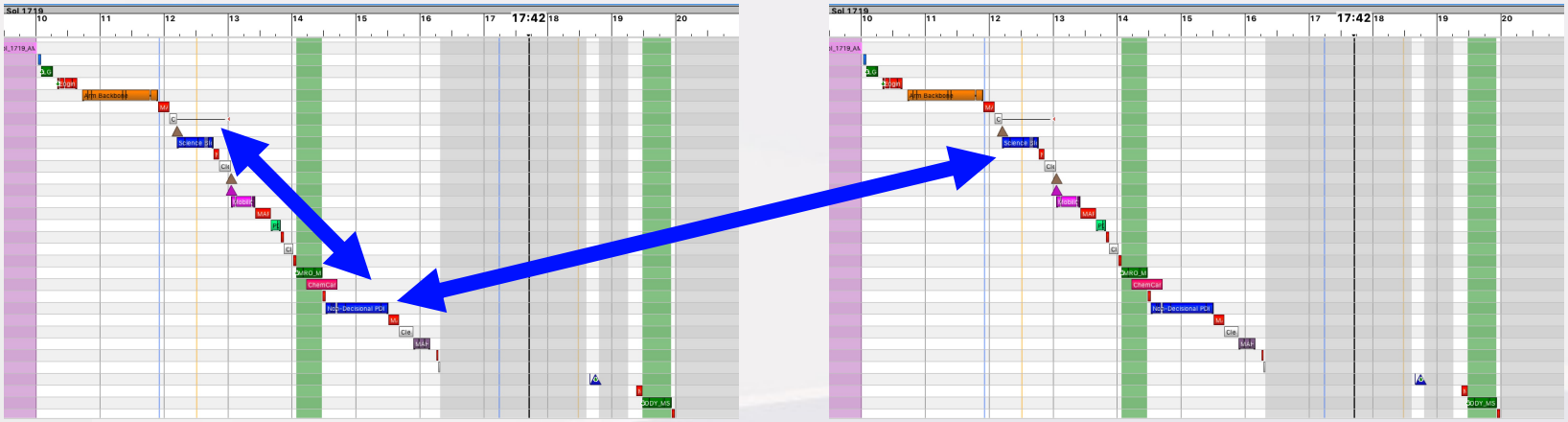
1) Upper, smooth material
2) Brighter vein
3) Lower, rough material

AEGIS had already measured the upper unit, allowing a complete survey with only 2 targeted measurements



New approaches

- Background bedrock survey along the rover's traverse
- Free up targeted time for other things
- Mitigate difficulties on the ground
- Making up for limited targetable time (contact science campaigns, engineering work)
- Following up tactically on serendipitous discoveries



AEGIS deployment & Ops team

AEGIS deployment relied on AEGIS, MSL, and ChemCam teams:

AEGIS
Tara Estlin (AEGIS PI)
Daniel Gaines
Raymond Francis
Gary Doran
Vandi Verma
Benjamin Bornstein
Michael Burl

And of course:
Larger AEGIS development team
ChemCam ops personnel
MSL engineering ops team
MSL science ops team

ChemCam
Roger Wiens (ChemCam PI)
Steven Johnstone
Suzi Montaño
Olivier Gasnault
Laurent Peret
Eric Lorigny
Diana Blaney
Jens Frydenvang
Valérie Mousset

MSL
Deb Chattopadhyay
Betina Pavri

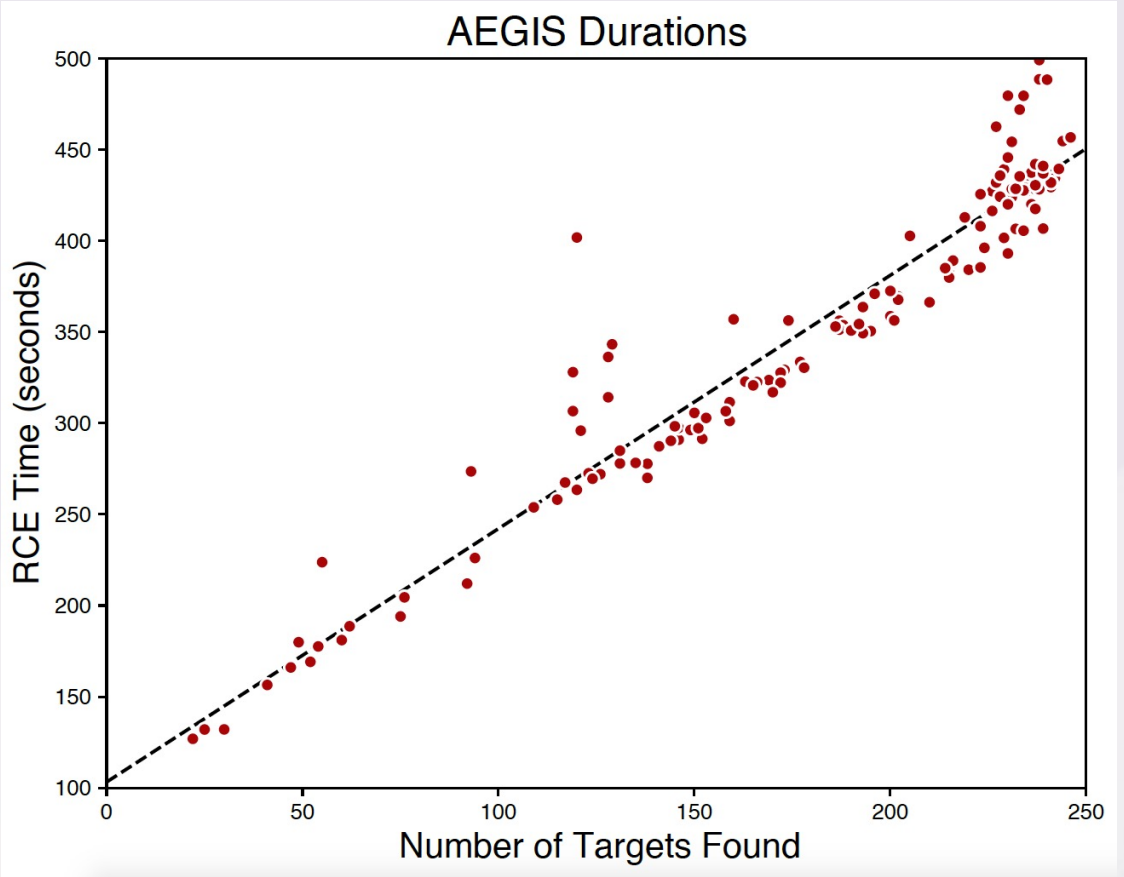
Run durations for NavCam

Run times on MSL flight RCE for AEGIS “Find Targets”: NavCam

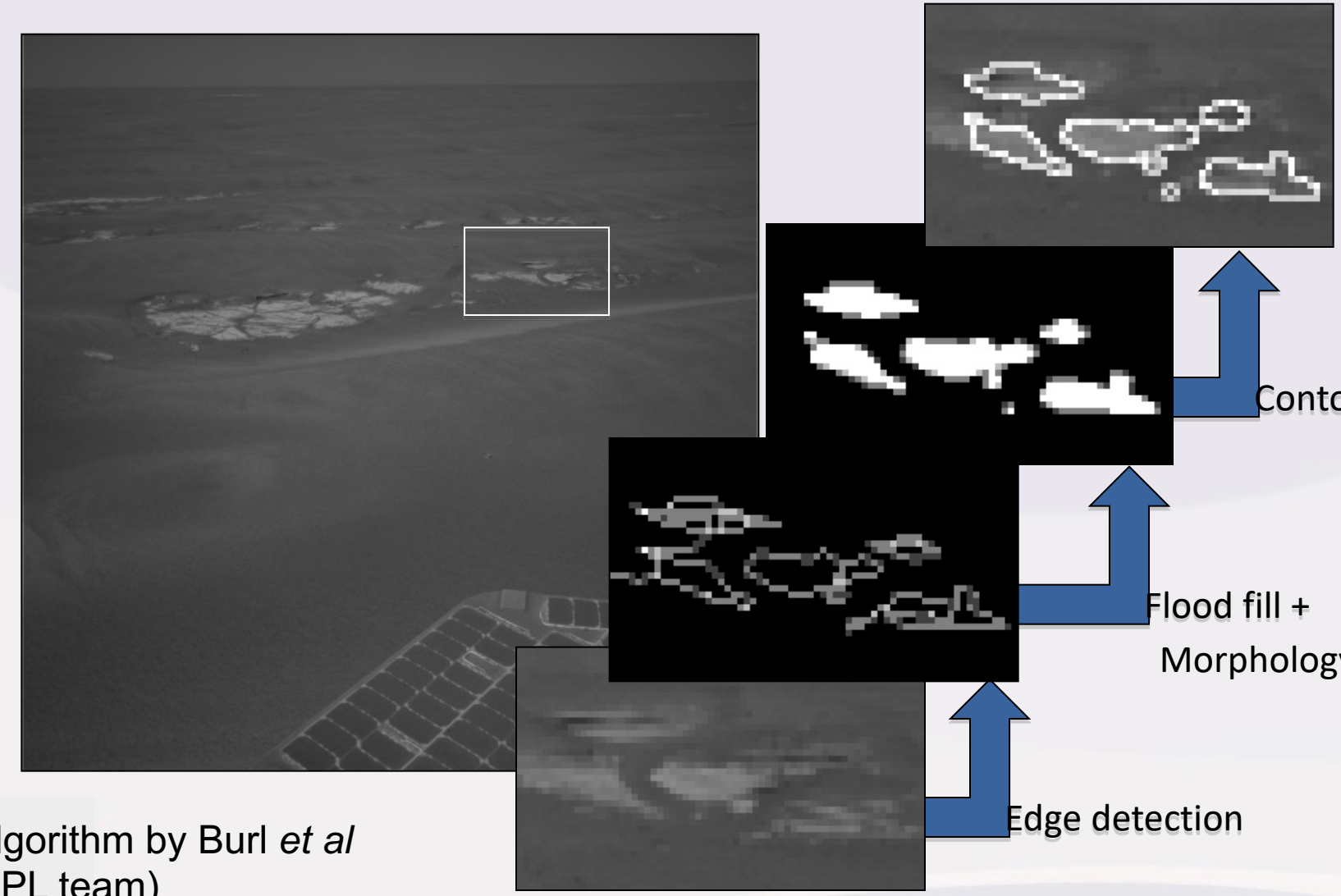
Roughly linear with number of targets found (90 s + 1.4 s per target, R=0.985)

Max duration: 488 seconds

Run times on MSL flight RCE for AEGIS “Find Targets”: RMI are about 95-105 seconds



AEGIS Target Detection using Rockster

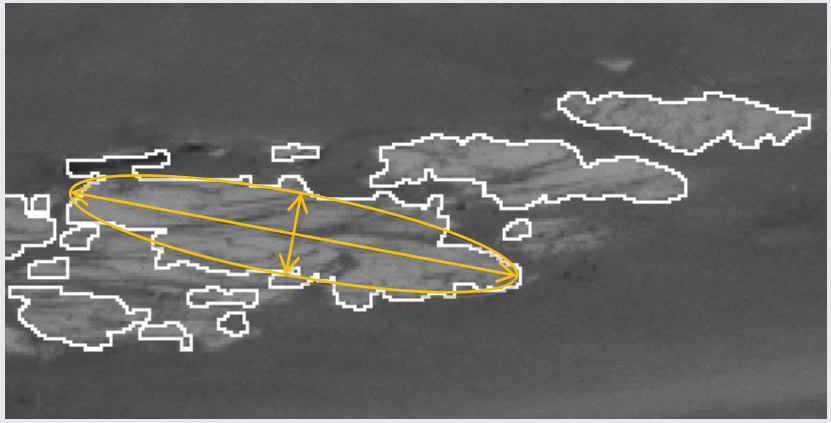


Algorithm by Burl *et al*
(JPL team)

Target Property Evaluation

Size

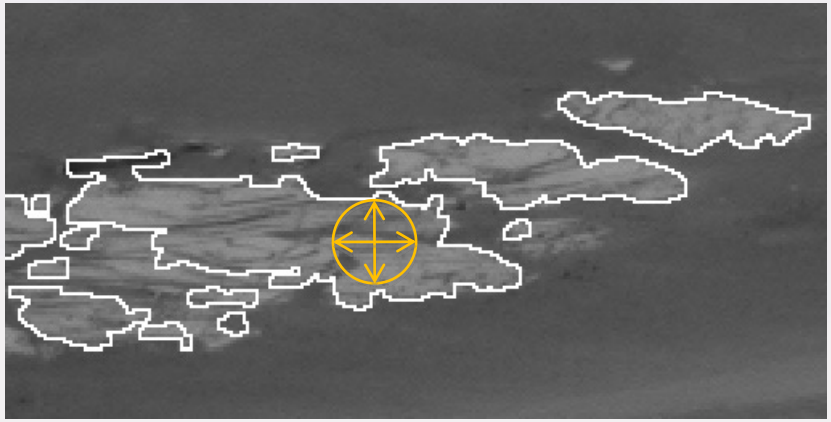
- Number of pixels
- 3D estimate (from stereo)
- Ellipse semi-major axis
- Ellipse semi-minor axis



Ellipse fit example

Position

- Distance from rover
- Inscribed circle x, y
- Site x, y, z
- Site az, el



Inscribed circle example

Target Property Evaluation

Intensity

- Mean
- Variance

Light Dark

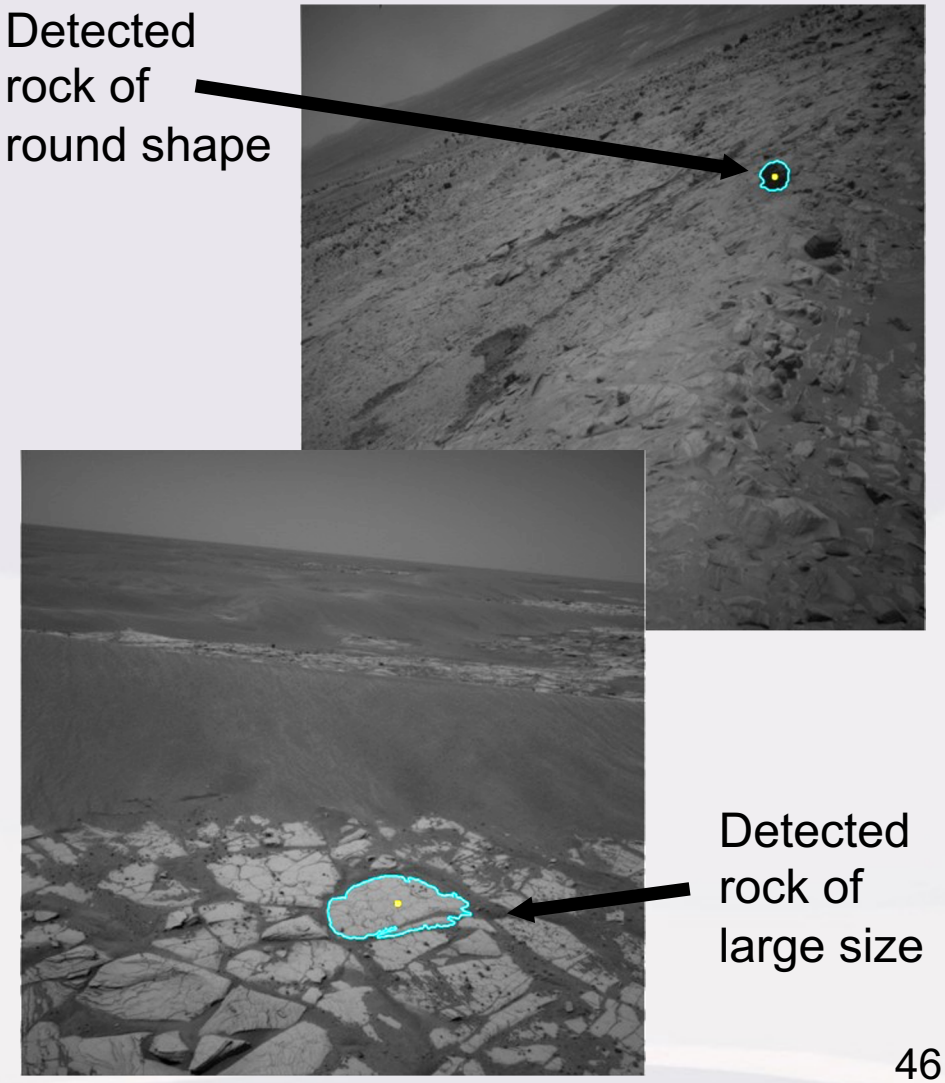
Shape

- Eccentricity
- Ellipse fit error
- Ruggedness
- Orientation

Rounded Angular

Target Prioritization

- Scientists can prioritize different property values
  - Single or combinations
  - e.g., prefer large, high albedo rocks
- Property setting is done at command sequencing
- Can be easily changed as rover enters different terrain areas
- Can support specific mission campaigns
  - E.g. cobble finder, outcrop finder

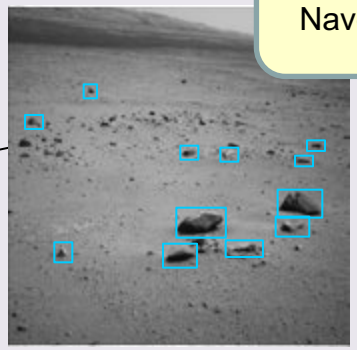


Onboard Process

Image pointing determined by ground.

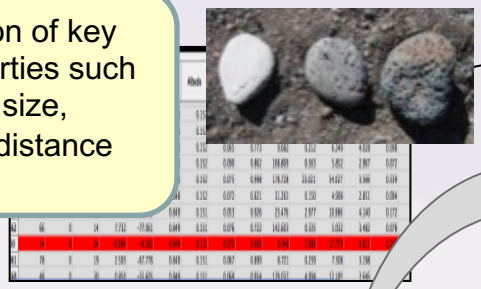
Navcam or RMI acquisition

Target detection



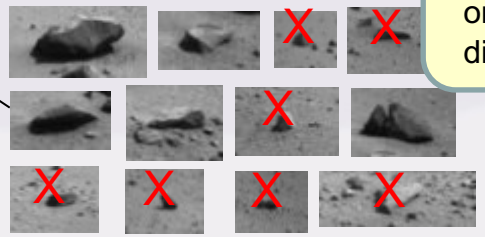
Detection of rock candidates in Navcam image.

Quantification of key target properties such as intensity, size, shape, and distance from rover.



Target feature extraction

Target filtering



Ops can filter targets based on size, distance, etc.

Ops can prioritize important properties for each run

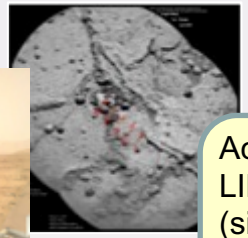
Top score for large size

Target prioritization

Set VTT frame to target position

Can repeat for multiple targets

CCAM raster acquired using VTT frame



Acquire ChemCam LIBS raster of target (size and direction pre-specified by ground)

Results: Target selection

Examples from the NavCam runs on the following slides…

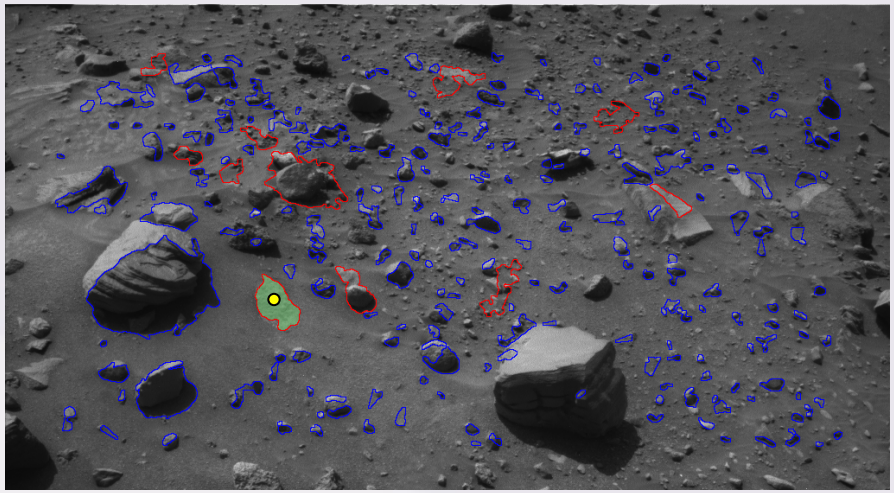
- Legend
  - Top target coloured in **green**
  - 2nd-ranked target coloured **orange** if observed
  - Targets retained after filtering: **red** outline
  - Targets found but filtered out: **blue** outline
    - Poor stereo range estimate, sun-safety, collision, outside ChemCam range, very small, very large

Results: Target selection

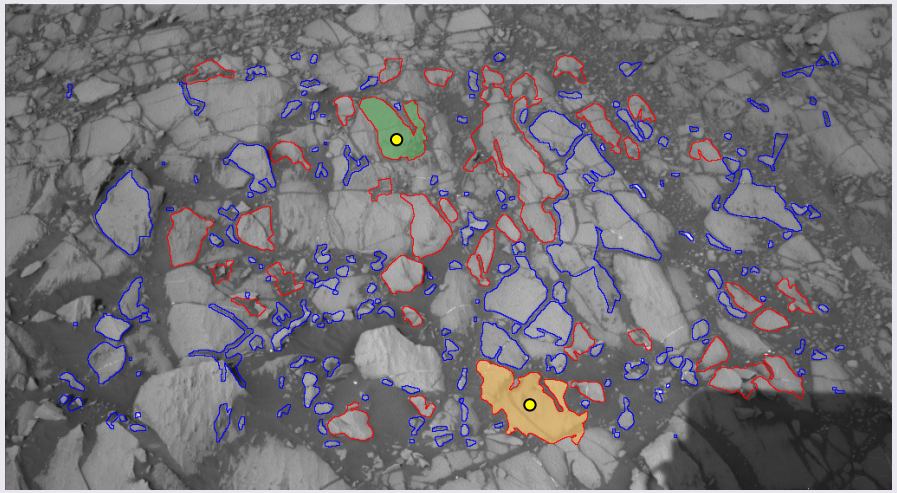
Examples from the NavCam runs on the following slides…

- Legend
  - Top target coloured in **green**
  - 2nd-ranked target coloured **orange** if observed
  - Targets retained after filtering: **red** outline
  - Targets found but filtered out: **blue** outline
    - Poor stereo range estimate, sun-safety, collision, outside ChemCam range, very small, very large
- **Keep in mind**
  - AEGIS' target-finding algorithm is searching for closed contours
  - Targets near the edge of the image are rejected for safety reasons
  - **What matters most is**:
    - Which target was picked?
    - Where did the LIBS shots end up?

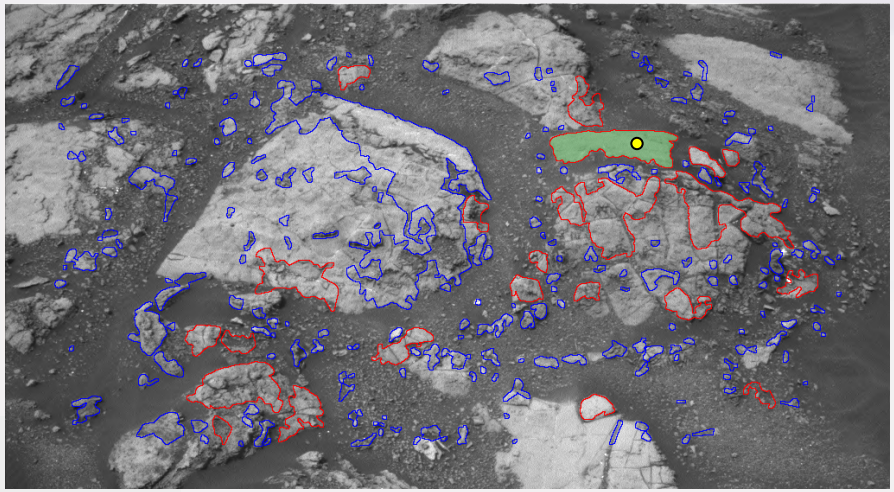
Results: Target selection



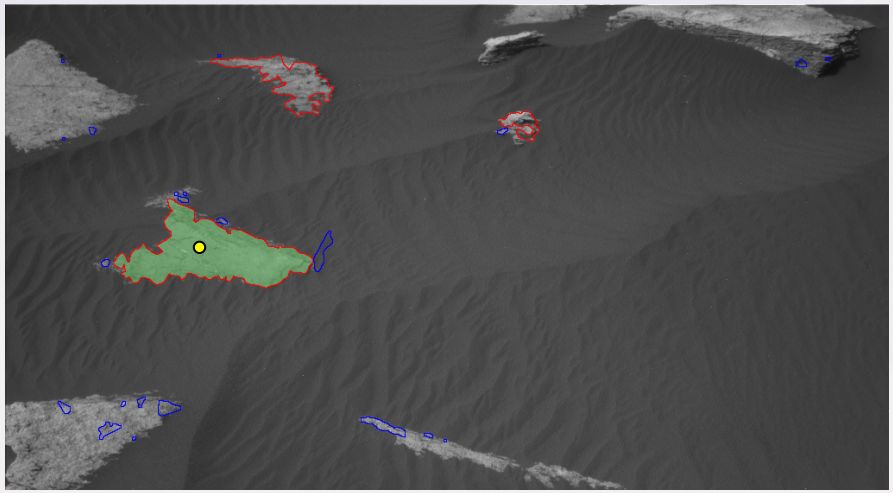
Sol 1400



Sol 1417

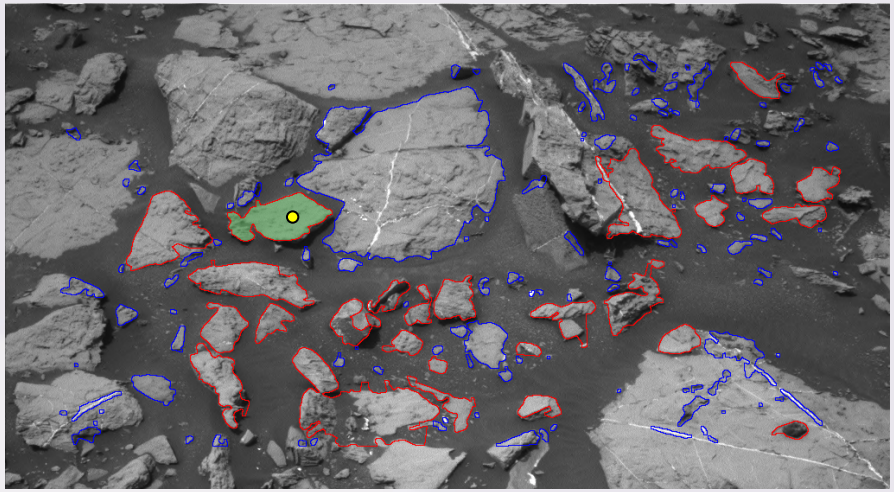


Sol 1481

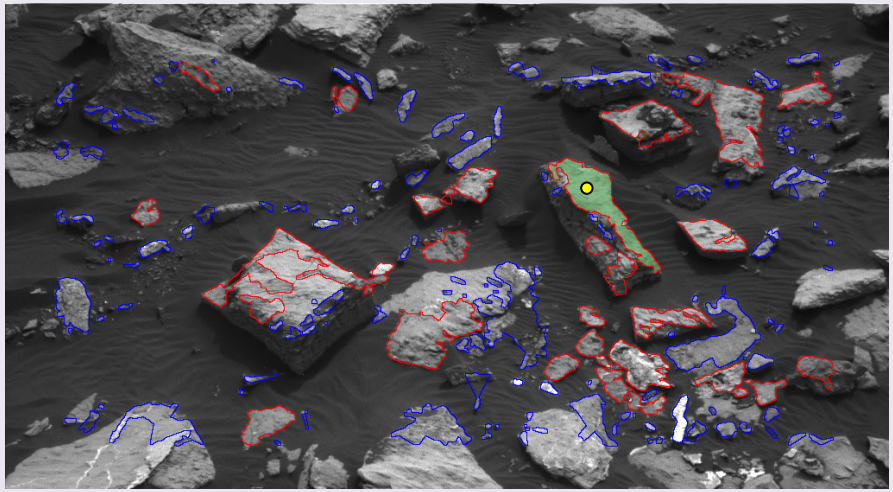


Sol 1636

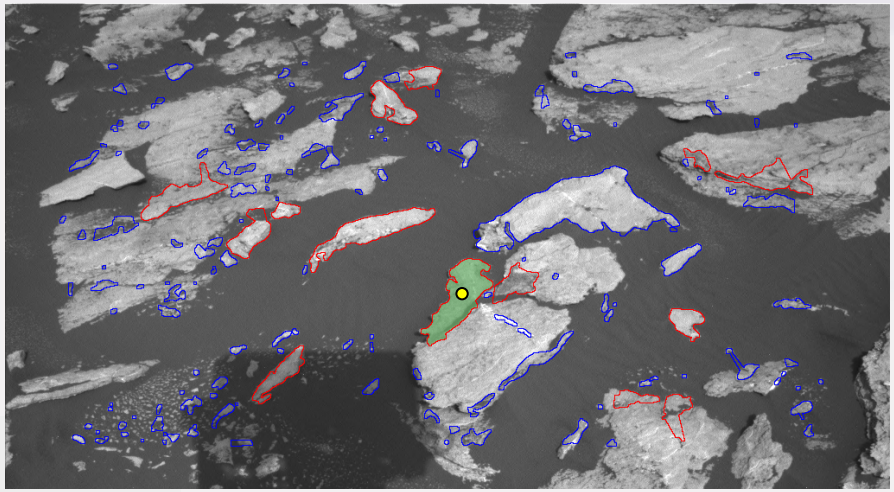
Results: Target selection



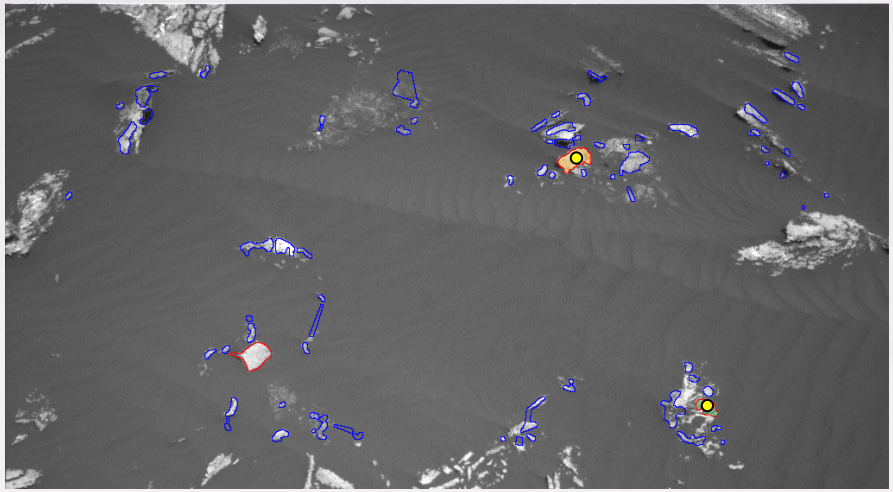
Sol 1449



Sol 1516



Sol 1605

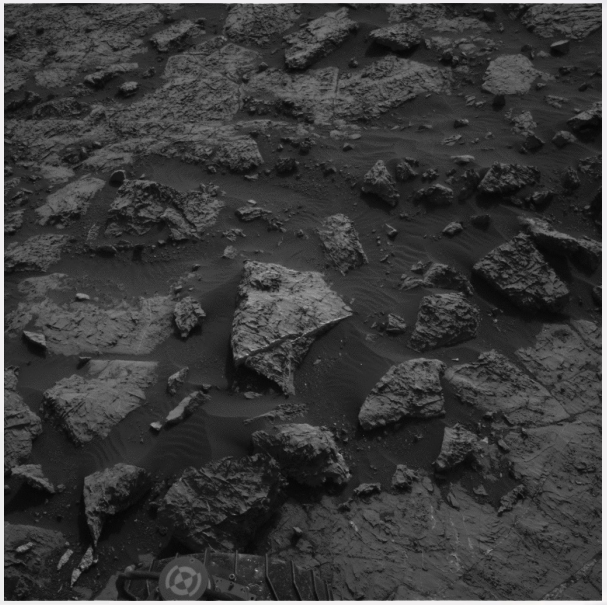


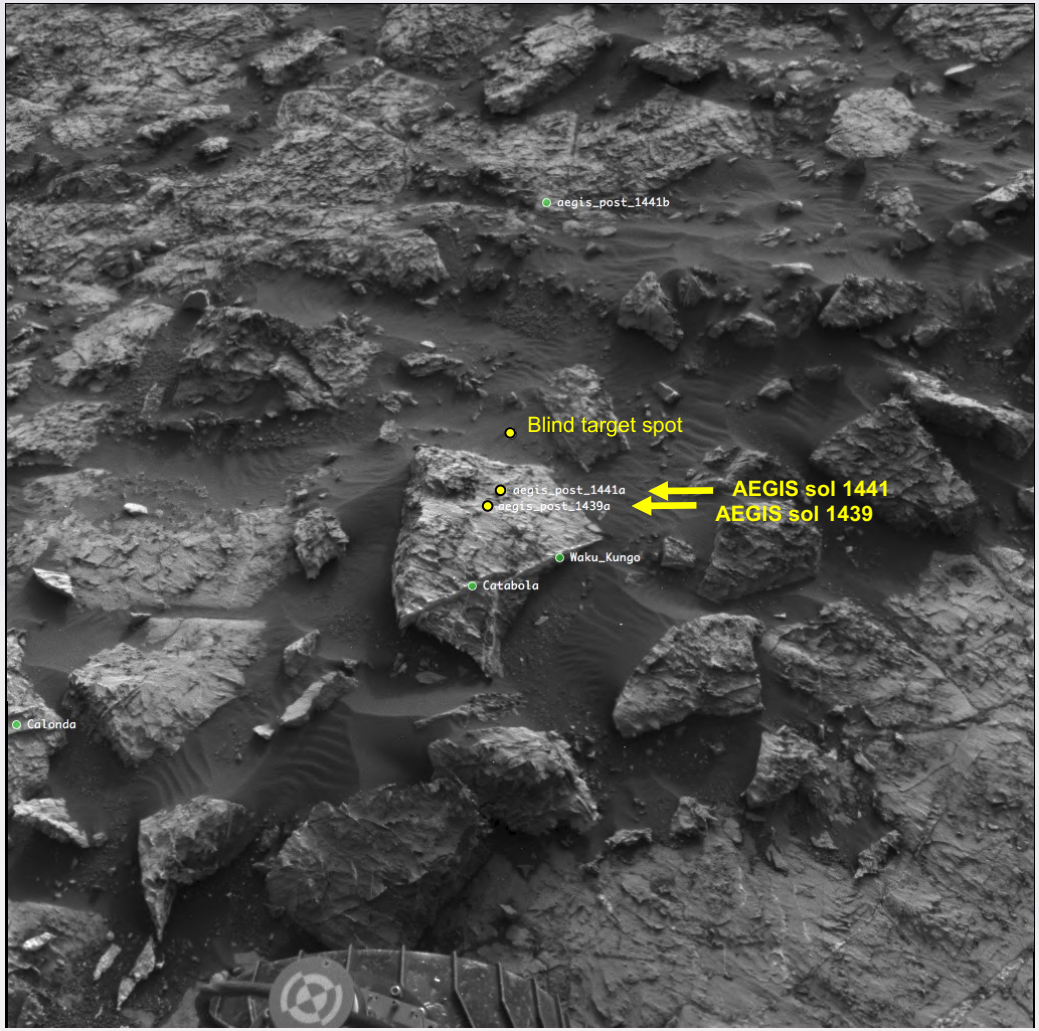
Sol 1660

Lighting robustness

Accidental vision experiment

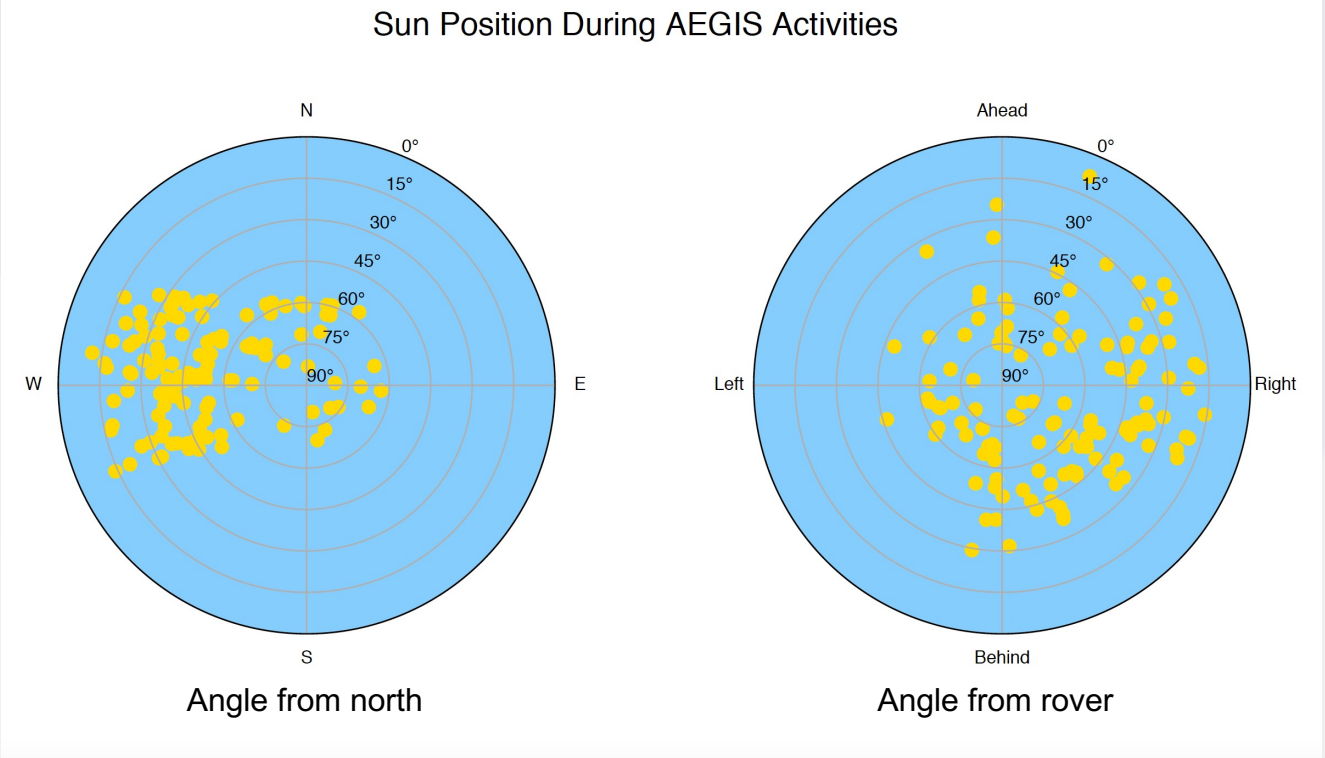
- Sol 1441 drive failed, so post-drive AEGIS FOV was nearly identical to sol 1439
  - Sol 1439: 15:40 LTST
  - Sol 1441: 16:49 LTST
- Despite shadows and small orientation change, top targets in each run are adjacent (same part of same block)





Lighting robustness

AEGIS autonomous targeting performs well across the range of lighting conditions we've seen



Solar elevation and angle (time of day)

Lighting direction and shadow orientation

Mars Science Laboratory

Discovering and exploring habitable environments in Gale Crater since 2012